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ABSTRACT

This booklet is one of the booklets in the "Understanding the Atom Series" published by the U. S. Atomic Energy Commission for high school science teachers and their students. Basic information for understanding the laser is provided including discussion of the electromagnetic spectrum, radio waves, light and the atom, coherent light, controlled emission, and the discovery of the laser. Other topics considered include interesting applications, the multitude of lasers, and communications. Numerous photographs and diagrams are utilized and a list of suggested references is included. (PR)

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ATOMIC ENERGY COMMISSION • UNITED STATES OF AMERICA •

The Understanding the Atom Series

Nuclear energy is playing a vital role in the life of every man, woman, and child in the United States today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them.

The United States Atomic Energy Commission provides this booklet to help you achieve such understanding.

Edward J. Brunenkant, Director
Division of Technical Information

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LASERS

ED055805

by Hal Hellman

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Division of Technical Information

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LASERS

By HAL HELLMAN

INTRODUCTION

The transistor burst upon the electronic scene in the 1950s. Almost overnight the size of new models of radios, television sets, and a host of other electronic devices shrank like deflating balloons. Suddenly the hard-of-hearing could carry their sound amplifiers in their ears. Teenagers could listen to favorite music wherever they went. Everywhere we turned the transistor was making its mark. There was even a proposal before Congress to require that every home have a transistor radio in case of emergency.

The next development to fire the imagination of scientists and engineers was the laser—an instrument that produces an enormously intense pencil-thin beam of light. Most of us have heard so much about this invention it seems hard to believe that the first one was built only a few years ago. We were told that the laser was going to have an even greater effect on our lives than the transistor. It was going to replace everything from dentists' drills to electric wires. The whole world, it seemed, eventually would be nothing but a gigantic collection of lasers that would do everything anyone wanted. Roads would be blazed through jungles at one sweep; our country would be safe once and for all from intercontinental ballistic missiles; cancer would be licked; computers would be small enough to carry in a purse; and so on and on.

Yet for the first couple of years the laser seemed able to do nothing but blaze holes in razor blades for TV commercials. Somehow the device never seemed to emerge from the laboratory, prompting one cynic to call it "an invention in search of an application".

Many of the wild claims came from misunderstandings on the part of the press, others from exaggerations by a few manufacturers who wanted free publicity. But with even less exotic devices than lasers, the road from the laboratory to the marketplace may often be long and hard. Price, efficiency, reliability, convenience—these are all factors that must be considered. It soon became clear that with something as new as the laser, much improvement was necessary before it could be used in science and medicine, and even more before it could be used in industry.

It now seems, however, that the turning point has been reached. We have seen laser equipment put on the market for performing delicate surgery on the eye, spot-welding tiny electronic circuits (Figure 1), and controlling machine tools with amazing accuracy (Figure 2).

Figure 1 *A commercial laser microwelder. A microscope is needed for accurate placement of beam energy.*

The pace is quickening. At least a dozen manufacturers have announced that they are designing laser technology into their products. These are not laboratory experiments but practical products for measurement and testing, and for industrial, military, medical, and space uses. The Army, for example, has announced that it will purchase its first equipment for use in the field: a portable, highly accurate range finder for artillery observation.

Still, this hardly accounts for the $100,000,000 spent in one recent year on laser research and development by some 500 laboratories in the United States. The U. S. Government alone has spent about $25,000,000 on laser research in a single year. Dozens, and perhaps hundreds, of other applications are on the fire—simmering or boiling as the case may be. Some require particular technical innovations such as greater power or higher efficiency. Others are entirely new applications. One of the most exciting of these is holography (pronounced ho LOG ra phy).

Holography involves a completely different approach to photography. In addition to more immediate applications in microscopy, information storage and retrieval, and interferometry, it promises such bonuses as 3-dimensional color movies and TV someday.

You have to see the holographic process in operation to believe it. One moment you are looking at what appears to be an underexposed or lightly smudged photographic plate. Then suddenly a true-to-life image of the original object springs into being behind the negative—apparently suspended in midair! Not only is the full effect of "roundness" and depth there, but you can also see anything lying behind the object's image by moving your head, exactly as if the original scene containing the object were really there.

Still another important field of application is that of communications. Perhaps because it is less spectacular than burning holes in razor blades, we haven't heard as much about it. Yet there are probably more physicists and engineers working on adapting the laser for use in communications than on any other single laser project.

The reason for this is the fact that existing communications facilities are becoming overloaded. Space on trans-

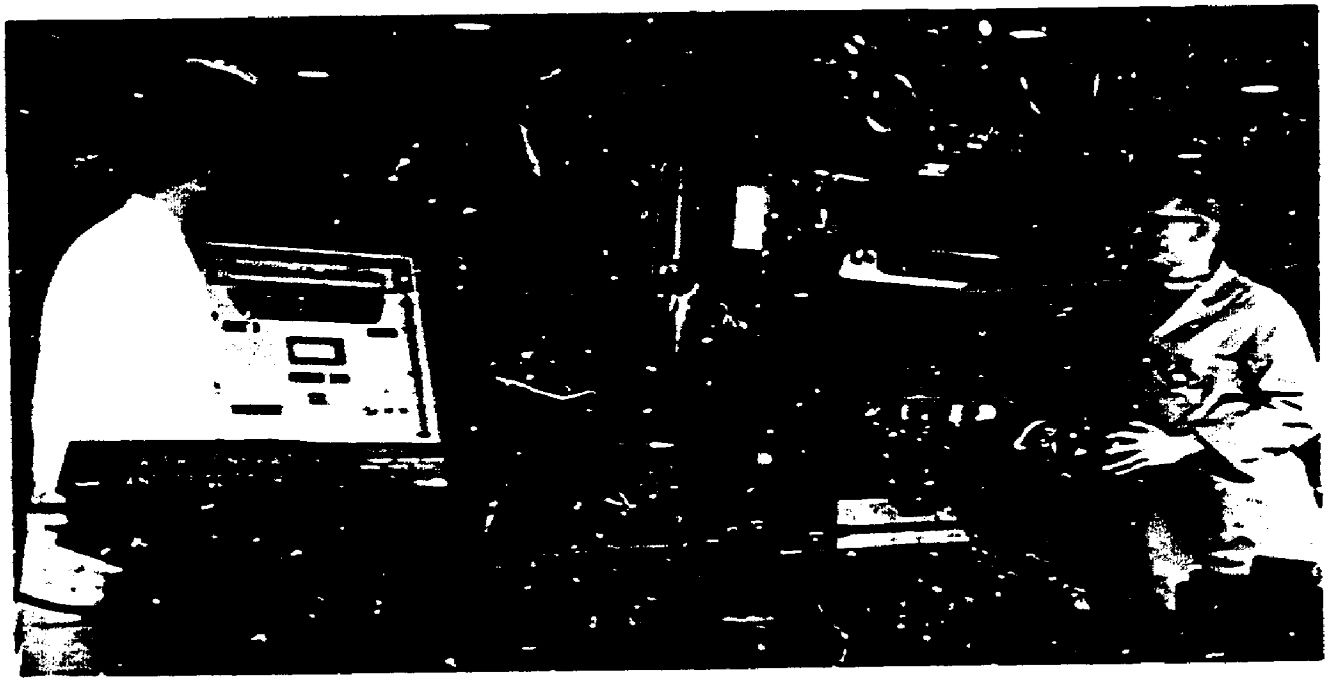

Figure 2 *Precision control of a machine tool by laser light.*

oceanic telephone lines is already at a premium, with waiting periods sometimes running into hours. Radio "ham" operators have been threatened with loss of some of their best operating frequencies to meet the demand of emerging nations of Africa for new channels. Television programs must compete for space on cross-country networks with telephone, telegraph, and transmission of data. The increasing use of computers in science, business, and industry will strain our facilities still further. Communication satellites will help, but they will not give us the whole answer; and much development work remains to be done on satellites.

Why the interest in the laser for communications? In a recent experiment all seven of the New York TV channels were transmitted over a single laser beam. In terms of telephone conversations, one laser system could theoretically carry 800,000,000 conversations—four for each person in the United States.

In this booklet we shall learn what there is about the laser that gives it so much promise. We shall investigate what it is, how it works, and the different kinds of lasers there are. We begin by discussing some of the more familiar kinds of radiation, such as radio and microwaves, light and X rays.

THE ELECTROMAGNETIC SPECTRUM

Some 85% of what man learns comes to him through his vision in response to the medium of light. Yet, ironically, it wasn't until the end of the 17th century that he first began to get an inkling of what light really is. It took the great scientific genius Isaac Newton to show that so-called white light is really a combination of all the colors of the rainbow. A few years later the Dutch astronomer Christiaan Huygens introduced the idea that light is a wave motion, a concept finally validated in 1803 when the British physician Thomas Young ingeniously demonstrated interference effects in waves. Thus it was finally realized that the only difference between the various colors of light was one of wavelength.

For light was indeed found to be a wave phenomenon, no different in principle from the water waves you have seen a thousand times. If you stand at the seashore, you can easily count the number of waves that approach the shore in a minute. Divide that number by 60 and you have the frequency of the wave motion in the familiar unit, cycles-per-second (cps).*

You would have to count pretty quickly to do this for light, however. Light waves vibrate or oscillate at the rate of some 400 million million times a second. That's the vibration rate of waves of red light; violet results from vibrations that are just about twice that fast.

With frequencies of this magnitude, discussion and handling of data and dimensions are cumbersome and rather awkward. Fortunately there is another approach. Let's look again at our ocean waves. We see that there is a regularity about them (before they begin to break on the shore). The distance from one crest to the next is significant and is called the *wavelength*. Water waves are measured in feet, and in comparable units light waves are recorded in ten-millionths of an inch—again a very cumbersome number. Scientists therefore use the metric

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*Sometimes referred to as *hertz* (abbreviated Hz), for the 19th Century German physicist Heinrich Hertz; 1000 Hz = 1000 cps.

system* and have standardized a unit called the angstrom†, which is equal to the one-hundred-millionth part of a centimeter (10^{-8} cm). Thus we find, as shown in Figure 3, that the visible light range runs from the violet at about 4000 angstroms to red at about 7000 angstroms.

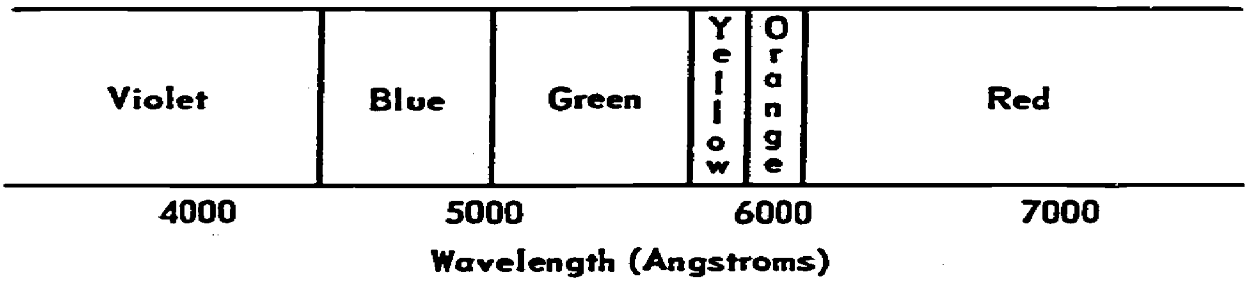


Figure 3 *The visible light spectrum ranges between approximately 4000 and 7000 angstroms.*

At roughly the same time that the wavelength of light was being determined, the German–British astronomer William Herschel performed an interesting experiment. He held a thermometer in turn in the various colors of light that had been spread out by an optical prism. As he moved the thermometer from the violet to the red, the temperature reading rose—and it continued to rise as he moved the instrument *beyond* the red area, where no prismatic light could be seen.

Thus Herschel discovered infrared rays (the kind of heat we get from the sun) adjoining the visible red light, and at the same time found that they were merely a continuation of the visible spectrum. Shortly thereafter, ultraviolet rays were found on the other end of the visible light band.

One of the most fascinating movements in science has been the constant expansion since then of both ends of the radiating-wave spectrum. The result has come to be called the *electromagnetic spectrum*, which, as we see in Figure 4, encompasses a wide variety of apparently different kinds of radiation. Above the visible band (the higher frequencies), we find ultraviolet light, X rays, gamma rays, and some cosmic rays; below it are infrared radiation, microwaves,

*Devised in France and officially adopted there in 1799, the metric system uses the meter as the basic unit of length and has been proposed for all measurements in this country.

† Named for the Swedish physicist Anders J. Angstrom.

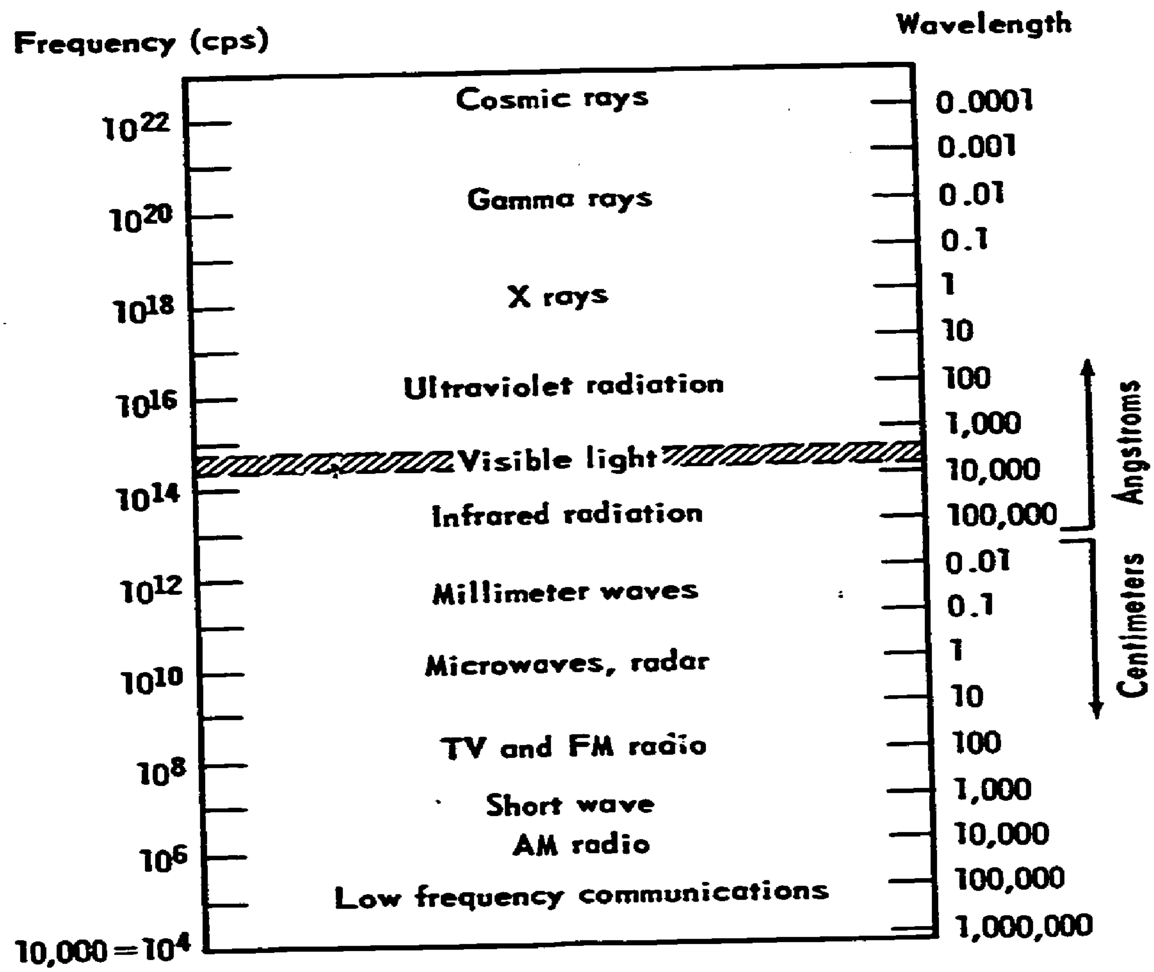


Figure 4 *Visible light region spans a tiny portion of the total electromagnetic spectrum.*

and radio waves. Only a small proportion of the total spectrum is occupied by the visible band. Another point of interest is the inverse relationship between wavelength and frequency. As one goes up the other goes down.*

These many kinds of rays and waves vary tremendously in the ways they interact with matter. But they are all part of a single family. The only difference among them, as with the colors of the rainbow, lies in their wavelengths. In a few cases, as we shall see later, the mode of generation is also different.

The band of radiation stretching from the infrared to cosmic rays has been, up to now, largely the concern of

* The wavelength, indicated by the Greek letter λ (lambda) is related to frequency (f) in the proportion λ (in meters) = 300,000,000/f. (The number 300,000,000 is the velocity of light in meters per second.)

physical scientists. Because of their high frequencies, these radiations are generally handled, when calculations or measurements must be made, in terms of wavelength. Radio and microwaves*, on the other hand, have been more in the domain of communications engineers and are more likely to be discussed in terms of frequency. Thus it is that your radio is marked off in kilocycles, or thousands of cycles per second, while light is described as radiation in the 4000 to 7000 angstrom band.

The relative newness of the various radiations has kept scientists busy learning about them and, as information and experience have accumulated, putting them to work.

*Microwaves are radio waves with frequencies above 1000 megacycles per second.

RADIO WAVES

One of the first of the newly discovered electromagnetic radiations to be put to work was the radio wave, which is characterized by long wavelength and low frequency.* The low frequency makes it relatively easy to produce a wave having virtually all its power concentrated at one frequency.

The advantage of this capability becomes obvious after a moment's thought. Think for example of a group of people lost in a forest. If they hear sounds of a search party off in the distance, all likely will begin to shout in various ways for help. Not a very efficient process, is it? But suppose all the energy going into the production of this noise could be concentrated in a single shout or whistle. Clearly, their chances of being found would be much improved.

The single frequency capability of radio waves has been given the name *temporal coherence* (or coherence in time) and is illustrated in Figure 5. Part *a* shows a single sine wave, the common way of representing electromagnetic

(a)

(b)

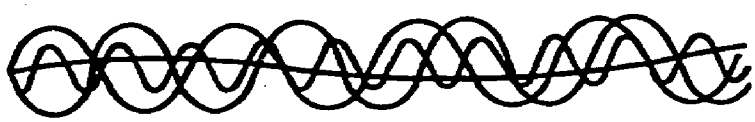


Figure 5 *(a) Temporally coherent radiation. (b) Temporally incoherent radiation.*

radiation, and particularly *temporally coherent radiation.* In *b* we see what *temporally incoherent radiation* (such as the mixed sounds of the stranded party) would look like.

It was on Christmas Eve 1906 that music and speech came out of a radio receiver for the first time. Today the sight

*Ten to 30,000,000 kilocycles per second; this is low in the electromagnetic spectrum, but not low in terms of the radio spectrum, which has a low-frequency classification of its own.

of someone walking, riding, or studying with an earpiece plugged into a transistor radio is common. But the early radio enthusiasts *had* to wear earphones because it takes considerable power to activate a loudspeaker and the received signal was quite weak. Some means of increasing, or amplifying, the signal was needed if the process was to advance beyond this primitive stage.*

The use of vacuum tube or electron tube amplifiers is so widespread that it is unnecessary to explain their operations here in any detail. It is important that the principle of amplification be understood, however. The input or information wave causes the grid to act as a sort of faucet as shown in Figure 6. That is, it controls the flow of electrons (the current in the circuit) from cathode to anode.

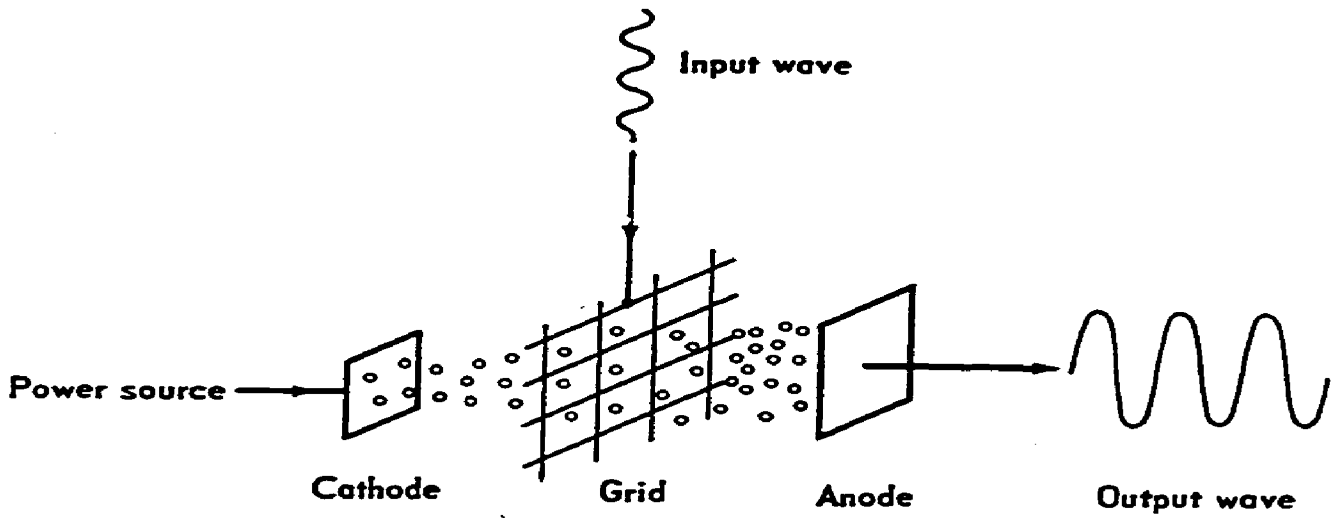


Figure 6 *Amplification by a three-element vacuum tube.*

A weak signal can therefore cause a similar, but much stronger, signal to appear in the circuit. The larger signal is subsequently used to power a loudspeaker in the radio set.

The amplification principle can be applied in another equally important way. Once a signal gets started in the circuit, part of it can be *fed back into the input* of the cir-

*Primitive as early radios were by today's standards, they brought a new era to communication at the time. Unmodulated CW (continuous wave) transmissions and crystal receivers were used to summon rescuers in the *Titanic* disaster of 1912, for example.

cuit. Thus the signal is made to go "round and round", continuously regenerating itself. The device has become an *oscillator*, that is, a frequency generator that produces a steady and temporally coherent wave. The frequency of the wave can be rigidly controlled by suitable circuitry.

The oscillator plays a vital part in radio transmission, for a transmitter beams energy continuously, not just when sound is being carried. The oscillator generates what is called a "carrier wave". Information, such as speech or music, is carried in the form of audio (detectable-by-ear) frequencies, which ride "piggyback" on the carrier wave. In other words, the carrier wave is *modulated*, or varied, in such a way that it can carry meaningful information. The familiar expressions AM and FM, for example, stand for Amplitude Modulation and Frequency Modulation—two different ways of impressing information on the carrier wave. Figure 7 shows a basic and an amplitude- (or height-) modulated wave.

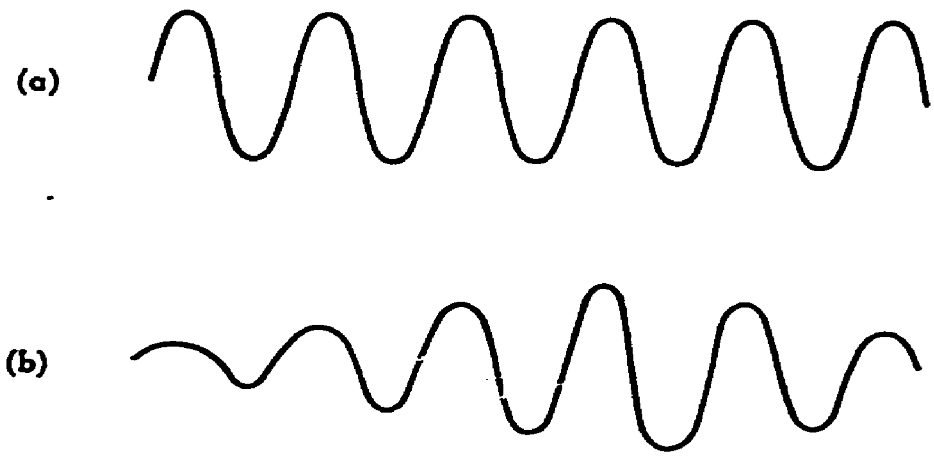


Figure 7 *(a) Unmodulated radio wave. (b) Amplitude-modulated wave carries information*

The electron tube made its giant contribution to radio, television, and other electronic devices by making it possible to generate, detect, and amplify radio waves.

Because radio waves are easily controlled, something useful can be done with them. Suppose we set up five radio transmitters, all beaming at the same frequency. The waves might look like those shown in Figure 8. Although the waves

are temporally (or time) coherent, they are out of step, and not *spatially coherent*. But since good control is possible in radio circuits, we can force each antenna to radiate in *phase* (that is, in step) with the others, thus producing fully coherent radiation (Figure 8b).

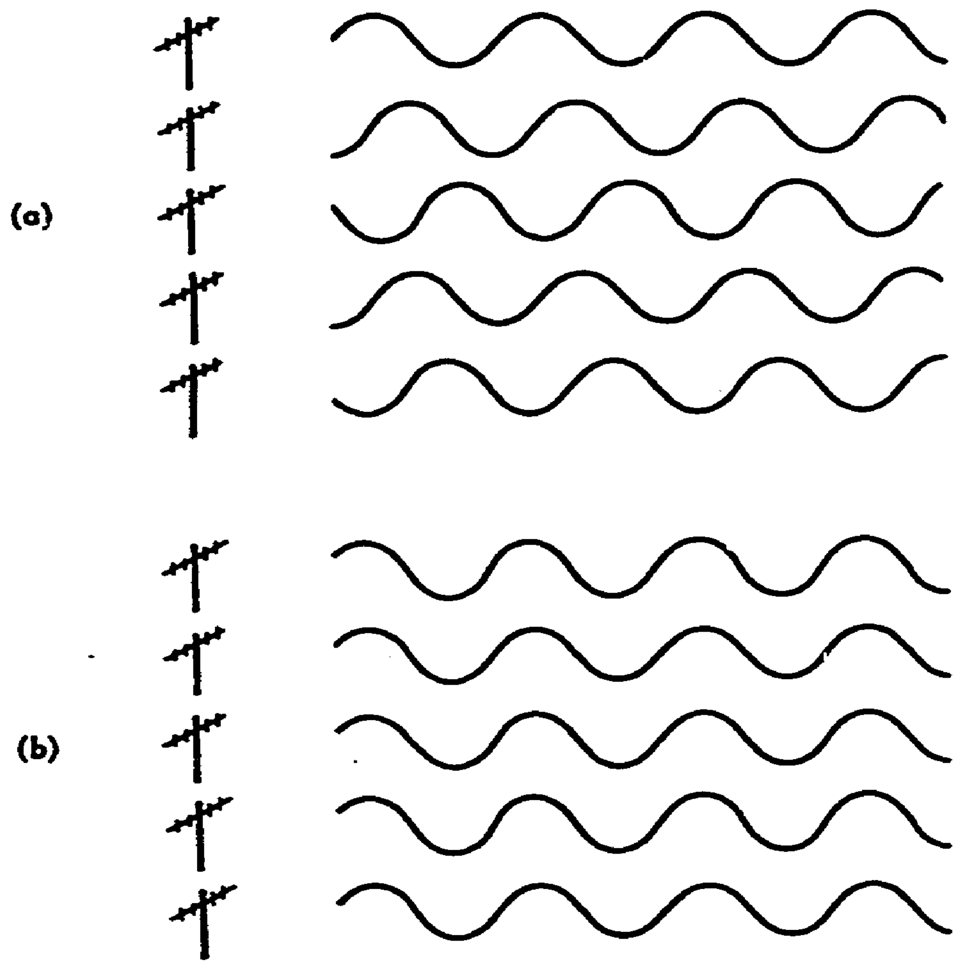


Figure 8 *(a) Spatially incoherent radiation. (b) Spatially coherent radiation.*

Such a process can increase the radiation *power* to an almost unlimited degree. But it does nothing to solve the problem of the limited total carrying capacity of the radio spectrum.

The most obvious and best way out of this difficulty is to raise the operating frequencies into the higher frequency bands. There are two reasons for this. First, it is clear that the wider the frequency band (the number of frequencies available) with which we work, the greater the number of communication channels that can be created.

But second, and more important, the higher the frequency of the wave, the greater is its information-carrying capacity. In almost the same way that a large truck can carry a bigger load than a small one, the greater number of cycles per second in a high frequency wave permits it to carry more information than a low frequency wave.

However, high frequencies must be generated in different ways than low frequency waves are; they require special equipment to handle them. Radio waves are transmitted by causing masses of free electrons to oscillate or swing back and forth in the transmitting antenna. (Any time electrons are made to change their speed or direction they radiate electromagnetic energy.)

Each kind of oscillator has some limit to the frequencies at which it can operate. The three-element electron tube has been successfully developed to oscillate at frequencies up to, but not including, the vibration rate of the microwave region. Here ordinary tubes have trouble for the unexpected reason that free electrons are just too slow in their reactions to oscillate as rapidly as required in microwave transmission.

To overcome this obstacle, two new types of electron tubes were developed: the klystron in 1938 and the traveling-wave tube some 10 years later. These lifted operation well up into the microwave region; it was the klystron that made wartime radar possible. Today many communication links depend heavily upon microwave frequencies.

At this point in our story we have a situation where low temporally coherent radio waves and microwaves can be generated, but nothing of higher frequency. Communications engineers have gazed wistfully, but almost hopelessly, at light waves, whose frequencies are millions of times higher than radio waves. Thus, just by way of example, some 15 million separate TV channels could operate in the frequency range between red and orange in the visible band.

What, then, is the problem?

Why is light so much more difficult to handle?

LIGHT AND THE ATOM

Since light waves have such high frequencies, a different mode of generation comes into play. We can no longer count on the controlled movement of free electrons *outside* atoms and molecules. Rather, light and all the radiations in the higher frequencies are generated by the movement of electrons *inside* atoms and molecules.

Let us review momentarily the modern, albeit highly simplified, conception of an atom. Remember that no one has yet seen one. We describe the atom on the basis of how it acts, as well as how it reacts to things scientists do to it.

For the present purpose, the best model we have of the atom is that of a miniature solar system, with a nucleus or heavy part at the center and a cloud of electrons dashing around the nucleus in fixed orbits.

The term "fixed orbits" is used advisedly.

Our planet moves in a certain orbit around the sun. If we attached a large enough rocket to the earth we theoretically *could* move it closer to or farther away from the sun. In the atom, we have learned, this cannot be done. An electron can only exist in one of a certain number of fixed orbits; different kinds of atoms have different numbers of orbits.

We might think in terms of an elevator that can only stop at the various floors of an apartment building. Each upper floor is like an orbit of the electron. But you get nothing for nothing in the world of physics, and just as it takes energy to raise an elevator to a higher floor, it takes energy to move an electron to an outer orbit.

Hence the atom is said to be raised to higher *energy* levels when an electron is nudged to an outer orbit. The energy input can be of many different kinds. Examples are heat, pressure, electrical current, chemical energy, and various forms of electromagnetic radiation. If too much energy is put into the elevator it goes flying out the roof. If too much energy is put into the atom, one or more of its electrons will go flying out of the atom. This is called *ionization*, and the atom, now minus one of its negative electrons and therefore positively charged, is called a positive *ion*.

But if the *right* amount of energy is put into the atom, one of its electrons will merely be raised to a higher energy level. Shown in Figure 9, for instance, are the ground state (Circle No. 1) and two possible higher energy levels. As you can see there are three possible transitions.

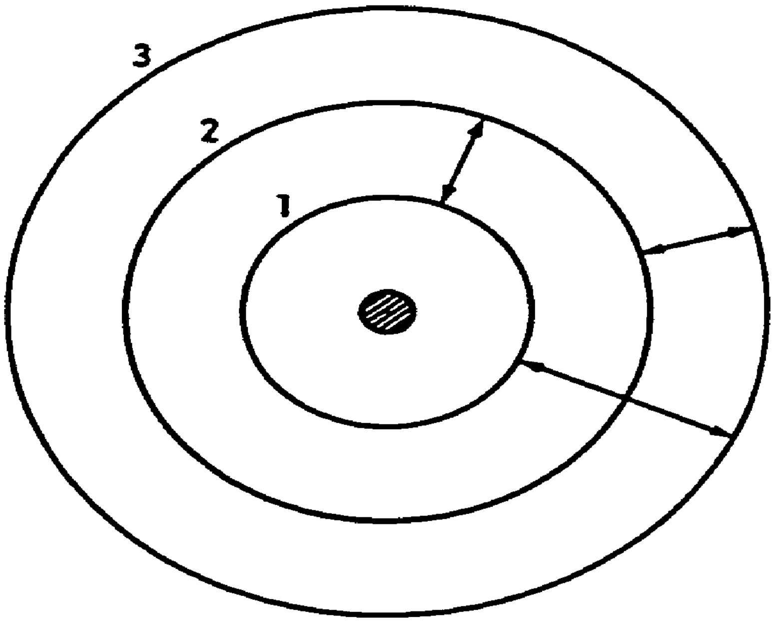


Figure 9 *Schematic representation of the electron orbits and energy levels of an atom. Each circle represents a separate possible orbit and each arrow a possible energy level difference.*

The higher energy levels are abnormal, or excited, states, however, and the electron will shortly fall back to its normal (ground state) orbit (assuming some other electron has not fallen into it first). In order for the electron to do this (go back to its normal orbit), it must give off the energy it has acquired. This it does in the form of electromagnetic radiation.

The energy difference between the two levels will determine what kind of radiation is emitted, for there is a direct correlation between energy and frequency.* If the energy difference between the two levels is such that the frequency of emitted radiation is roughly between 10^{14} and 10^{15} cycles per second, we see the radiation as light. When

*Energy = h (Planck's constant) × frequency. Planck's constant is the energy of 1 quantum of radiation, and equals 6.62556×10^{-27} erg-sec.

more energy is added, the radiation emerges as ultraviolet or X rays. In other words the higher the energy difference, the higher the frequency, and vice versa. Thus it is that cosmic rays, with the highest frequencies known to man, can pass right through us as if we weren't there.

This simple picture of energy levels and associated frequencies doesn't quite hold for ordinary white light, however. Such light is generally produced by a process called incandescence, which results from the heating of a material until it glows. True, the atoms of the incandescent material are being raised to higher energy levels by chemical energy (as in fire), electricity (light bulb), or nuclear energy (the sun). In a hot solid, however, the explanation becomes more complicated. Many different electronic configurations are possible and the differences in energy among the various levels (which can be many more than the three shown in Figure 9) vary only slightly from one another. The result is a wide band of radiation.

Thus, while the incandescent electric bulb is a great advance over fire, it is still a very inefficient source of light. Because it depends upon incandescence, a considerable portion of the electrical input goes into the production of unwanted heat, for the bulb's filament radiates in the infrared as well as the visible region.

For providing illumination, the fluorescent tube is far more efficient than the incandescent lamp: a 40-watt fluorescent tube gives as much light as a 150-watt incandescent light. This is because its radiation is more controlled, operating more in accord with our description of electronic energy levels. Hence more of its output is in the desired visual region of the spectrum.

In certain types of lighting, particular energy level changes may predominate, leading to the characteristic colors of neon tubes and vapor lamps. Although the resulting radiation bandwidth is narrow enough in these devices to appear as a definite color instead of the broad spectrum we know as white, it is still quite broad. In other words, the radiation is still frequency incoherent—and it is still spatially incoherent.

To understand this, let us return for a moment to the group of radio antennas we showed in Figure 8. All of

them, you will recall, could be made to radiate in phase. In the production of light, however, each antenna is replaced by a single atom!

This creates two problems. First, because the energy stored in the atom is quite small, it comes out not as a continuous wave but as a tiny packet of radiation—a *photon.** It has an effect more like the hack of an ax than the buzz of a power saw.

Second, atoms are notoriously "individualistic". When a batch of atoms in a material has been raised to higher energy levels there is no way to know in what order, or in what direction, they will release their energy.

This kind of process is called *spontaneous emission*, since each atom "makes up its own mind". All we know is that within a certain period of time—a short period, to be sure—a certain percentage of these higher energy atoms will release their photons.

What we have, then, is incoherent radiation—a jumble of frequencies (or colors), directions, and phases. Such light, symbolized in Figure 10, works well enough in lighting up this page, but is almost worthless as a carrier of information (and in other ways, as we shall see shortly). About the best that can be done with it is to turn it on and off in a sort of visual Morse code, which is exactly what is done on the blinker communication systems sometimes used for ship-to-ship communication.

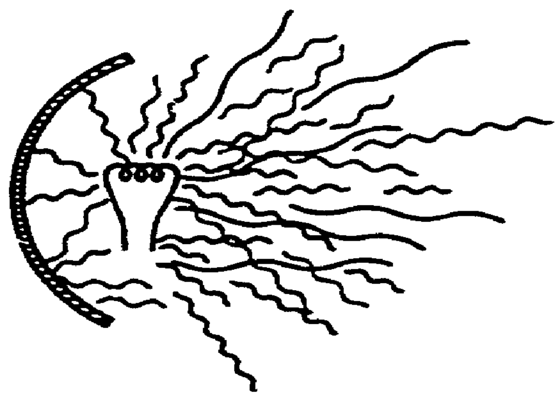


Figure 10 *Ordinary light is a jumble of frequencies, directions, and phases.*

In other words, ordinary light cannot be modulated as radio waves can.

It is of interest to note, however, that ordinary white light *can* be made coherent, to some extent, but at a very

*Each photon carries 1 *quantum* of radiation energy, which is a unit equal to the product of the radiation frequency and Planck's constant (see footnote page 15).

high cost in the intensity of the light. For example, we might first pass the light through a series of filters, each of which would subtract some portion of the spectrum, until only the desired wavelength came through. As can be seen in Figure 11, only a small fraction of the original light would be left.

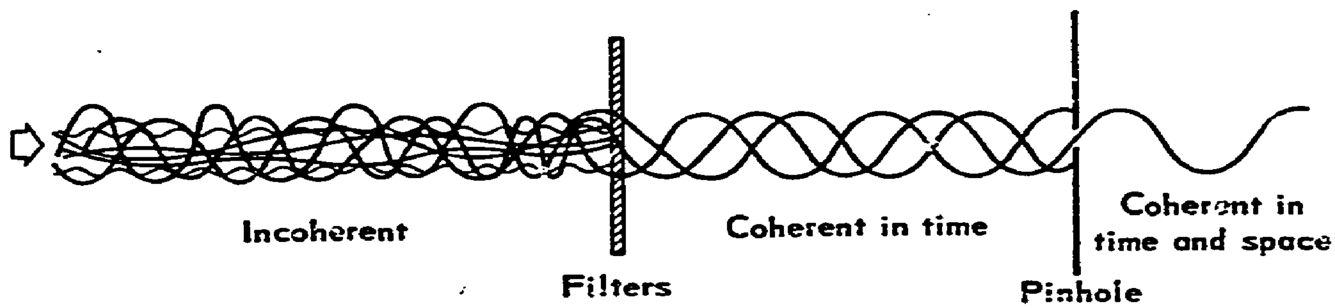


Figure 11 *Obtaining coherent radiation the hard way. Filters and pinhole block all but a small amount of the original radiation.*

We would then have monochromatic (one color) light, which is temporally coherent radiation, but it would still be spatially incoherent. In our diagram, we show three monochromatic waves. If we then passed this light through a tiny pinhole as shown, most of these few remaining waves would be blocked; the ones that got through would be pretty much in step. (In a similar manner, a true point source of light would produce spatially coherent radiation; but, as in the process described here, there wouldn't be very much of it.)

We have, finally, obtained coherent light.

The important thing about the laser is that, by its very nature, it produces coherent light automatically.

Now...

WHAT'S SO SPECIAL ABOUT COHERENT LIGHT?

So desirable are the qualities of coherent light that the complicated filtering process described above has actually been used. For example, one British experimenter, Dennis Gabor, used it in the 1940s in an attempt to make a better microscope. But so great was the effort, and so meager the resulting light, that this project was abandoned.

In the course of Dr. Gabor's experiments, however, he did manage to make a special kind of picture, using coherent light, which he called a *hologram*. He derived the name from two Greek words meaning a *whole picture*. We shall see why in a moment.

Ordinary black and white photographs merely record darks and lights, or the intensity of the illumination, thereby providing a scale of grays, nothing more. But because waves of coherent light consistently maintain their relative spacing, they can be used to record additional information, namely the distance from objects.

For example, if we shine a beam of coherent (laser) light between two objects we can, knowing the light wavelength, determine the distance between them to a high degree of accuracy. The basic idea is diagramed in Figure 12. It can be seen that the number of waves times the wavelength gives the precise distance (to within 1 wavelength of light) from the laser source to each object. But this would be a difficult process to implement.

A better way, and one that is already in operation, is to use conventional methods to measure the approximate distance and use the laser beam for precise or fine measurement. In the device shown in Figure 2, the beam is split into two parts. One part is kept in the instrument itself to act as a reference. The other is aimed at a reflector, which sends it back to a detector in the main device, where it is automatically compared with the reference beam. If the two beams are in phase (that is, if their crests are superimposed), the waves combine and produce a high intensity beam at the detector. As the reflector moves closer to or farther away from the laser source the beam intensity decreases and then increases

again as the wave crests move in and out of phase. The instrument counts the changes and displays the distance the reflector moves, as a function of the wavelengths, on the control cabinet meters.

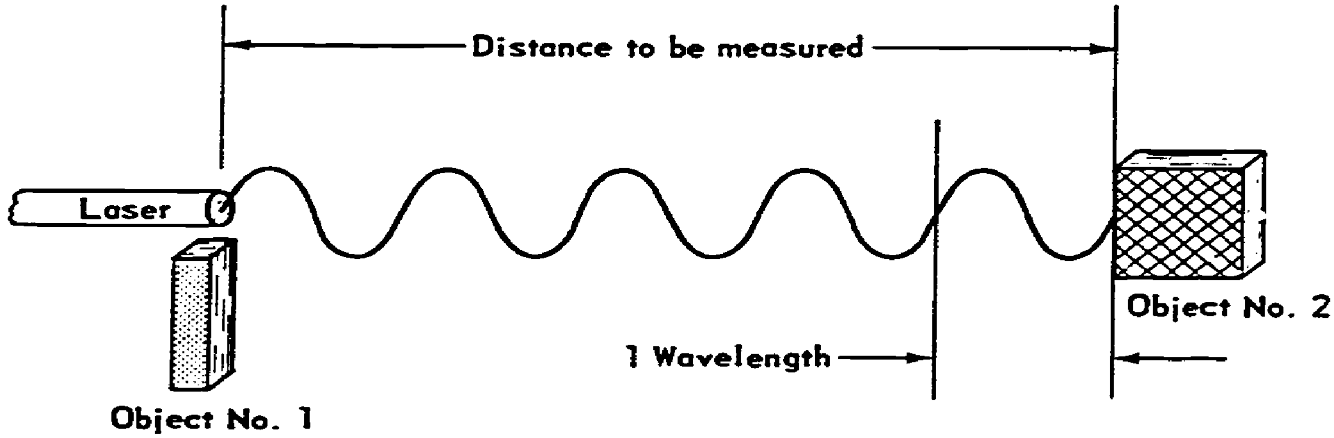


Figure 12 *Principle of distance measurement using coherent light. Wavelength times number of waves gives precise distance between laser and object.*

Since the word for the interaction of the waves in a system like this is "interference", the measurement process is called *interferometry* (pronounced in ter fer OM e try). Although not new, it can now be applied for the first time in machine tool applications, providing the accuracy needed in this age of space technology and microminiaturization. Measurements with a laser interferometer can be made with an accuracy of 0.5 part per million at distances up to 200 inches. Such precision was previously unheard of in a machine shop environment, having been limited to laboratory measurements, and only at a range of a few inches. Under similar laboratory conditions, measurements by laser interferometry now detect movements of 10^{-11} centimeter, a distance approaching the dimensions of an atomic nucleus.

Now let us suppose we expand the laser beam as shown on page 22, and, with the aid of a mirror, direct part of it (the reference beam) at a photographic plate. The remaining portion of the diverging beam is used to illuminate the object to be photographed. Some of this light (the object beam) is reflected toward the plate and carries with it information about the object, as indicated by the wavy line.

In the region where these two beams intersect, interference occurs, and a sample of this interference is recorded within the photographic emulsion. Where two crests meet a dark spot is recorded; where the waves are out of phase the processed plate is clear. The result is a hologram, a complex pattern of "fringes", characteristic of the contour and light and dark areas of the object, as well as its distance from the plate. These fringes have the ability to diffract light rays. When light from a laser, or a point source of white light, is directed at the hologram from the same direction as the reference beam, part of the light is "bent" so that it appears to come from the place once occupied by the object. The result is a remarkably realistic 3-dimensional image.

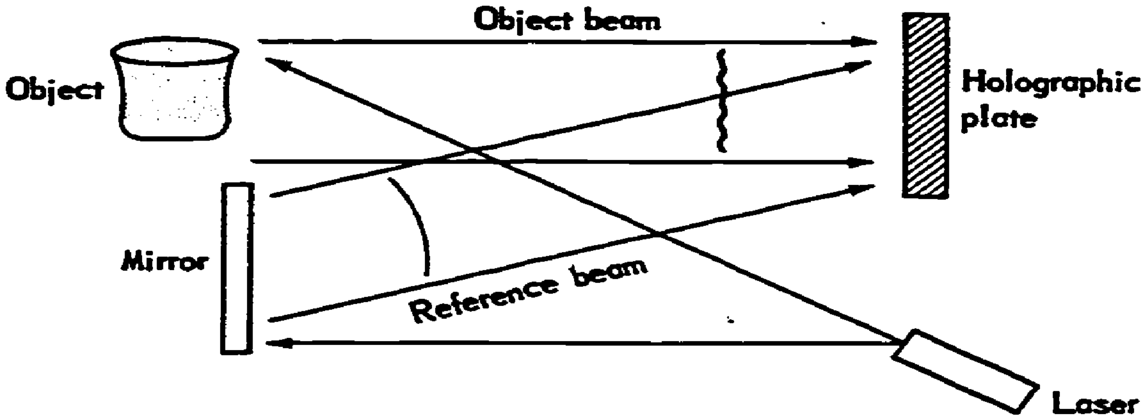
There, in a nutshell, is the incredible new technique of holography. The extreme order of laser light is illustrated by the regularity of the dots on the cover of this booklet.

This strange kind of light provides us with yet other advantages. Indeed, one of the most important is the fact that the energy of the laser is not being sprayed out in all directions. All of it is concentrated in the narrow beam that emerges from the device. And it *stays* narrow. Laser light has already been shone on the moon, the beam spreading out to only a few miles in traveling there from earth. The best optical searchlight beam would spread wider than the moon itself, thus dissipating its energy.

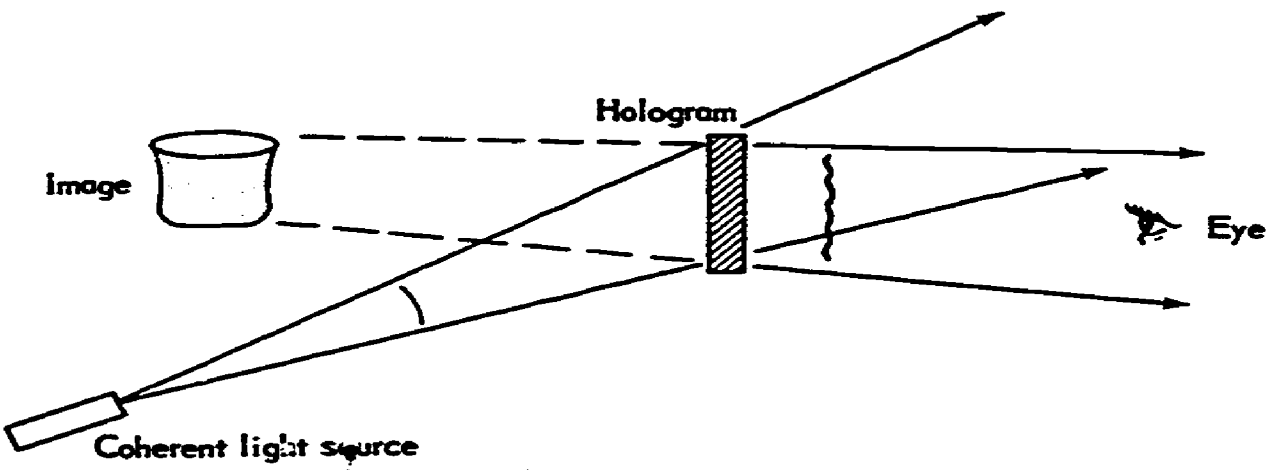
It is for this reason, as well as its temporal coherence, that laser light is being considered for communications. A narrow beam is particularly important for space communications because of the long distances involved.

But it is also possible to focus laser light as no light has ever been focused before. At close range a laser beam can be focused down to a circle just a few wavelengths across, concentrating its energy and making it possible to drill holes only 0.0002 inch in diameter. The photo on page 52 shows the exquisite control that can be exercised.

Let us see what this focusability means in terms of power. Consider, by way of analogy, a dainty 100-pound lady in a pair of spike-heeled shoes. As she takes a step, her weight will be concentrated on one of those heels. If the area of the heel is, say, one quarter of a square inch



MAKING A HOLOGRAM



VIEWING A HOLOGRAM

($\frac{1}{2} \times \frac{1}{2}$ inch), the pressure exerted on the poor tile or carpet rises to 400 pounds per square inch (4×100) and if the heel is only $\frac{1}{4}$ inch on a side, the pressure will be 1600 pounds per square inch!

What we are getting at, of course, is the fact that the coherence of the laser beam permits it to be concentrated into a tiny area. Thus whatever total energy is being sent out by the laser can be concentrated to the point where its effective energy is tremendous. The sun emits some 6500 watts per square centimeter. Laser beams have already reached 500 *million* watts per square centimeter.

But the power of the laser does not derive solely from its ability to be focused. Even an unfocused beam is several times more powerful than the sun's output (per square centimeter).

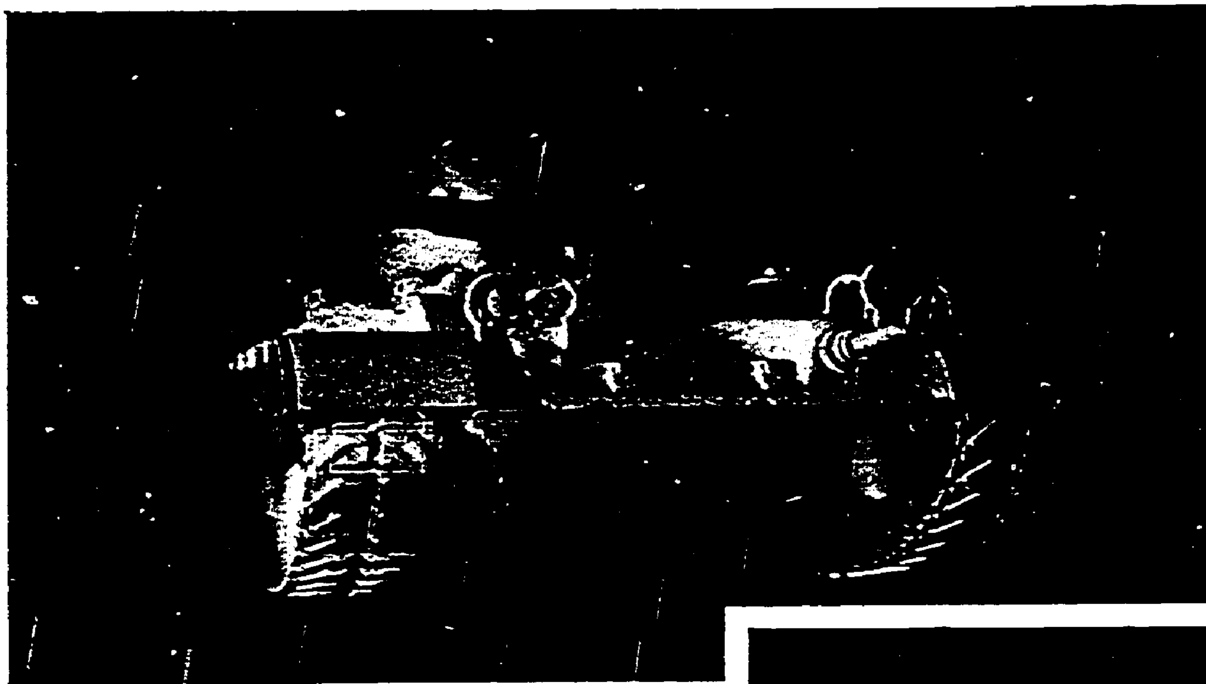


Figure 13 *The typical hologram, on the right, looks like a geometric design, but it contains more information than would an ordinary photograph. The images above and below, made from a hologram, show the detail, apparent solidity, and parallax effect of the reconstructed light waves. The parallax effect is the ability to see around the objects just as one could if they were really there. (See frontispiece.)*

The crucial difference between the sun's light or any ordinary kind of light and laser light lies in the extent to which the emission of energy can be controlled. In the production of ordinary light the atoms, as we know, emit spontaneously, or in an uncontrolled fashion. But if the atoms could be forced to take in the proper amount of energy, store it, and release it when we wanted them to, we would have *stimulated*, rather than spontaneous, emission.

This, however, is practically the same as the amplification principle we discussed earlier. In that case, a small radio signal is jacked up into a large one by stimulating an available power source to release its energy at the same wavelength and in step with the smaller signal.

The question is, how can we do this with light?

CONTROLLED EMISSION

The laser and its parent, the maser, can be traced back half a century to its theoretical beginnings. The great physicist Albert Einstein is most widely known for his work in relativity. But he did early and important work on that other gigantic 20th century scientific achievement, the quantum theory.* In one of his papers, published first in Zurich, Switzerland, in 1916, Einstein showed that controlled emission of light energy could be obtained from an atom under certain conditions. When an atom or molecule has somehow had its energy level raised, the release of th s stored energy could be stimulated by subjecting the atom or molecule to a small "shot" of electromagnetic radiation of the proper frequency.

Einstein wrote that when such a photon of energy caused an electron to drop from a higher to a lower orbit, the electron would emit another photon of the same frequency and in the same direction as the one that hit it.† In other words, the energy of the emitted photon would be added to that of the photon that stimulated the emission in the first place. Here, *potentially*, was light amplification. The three major factors, absorption of energy, spontaneous emission, and stimulated emission are diagrammed in Figure 14.

There the matter lay for more than 30 years.

In 1951 Charles H. Townes, then on the Columbia University faculty, was interested in ways of extending to still higher frequencies the range of microwaves available for use in communications and in other scientific applications. Townes and other scientists who were interested in the problem were to meet in Washington, D. C., on the 26th of April. The night before the meeting he slept in a small Washington hotel; but he awoke at 5:30—pondering, pondering the high frequency problem.

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*Einstein was awarded the Nobel Prize in 1921 for his 1905 explanation of the photoelectric effect (in terms of quanta of energy) and *not* for his relativity theory.

†Einstein's theoretical explanation applies in the case of stimulation of a single atom. In practical stimulation, directionality is enhanced by stimulating many atoms in phase.

He dressed and took a walk, then sat on a park bench and savored the beauty of azaleas in bloom. But all the while his mind was running over the various aspects of the problem.

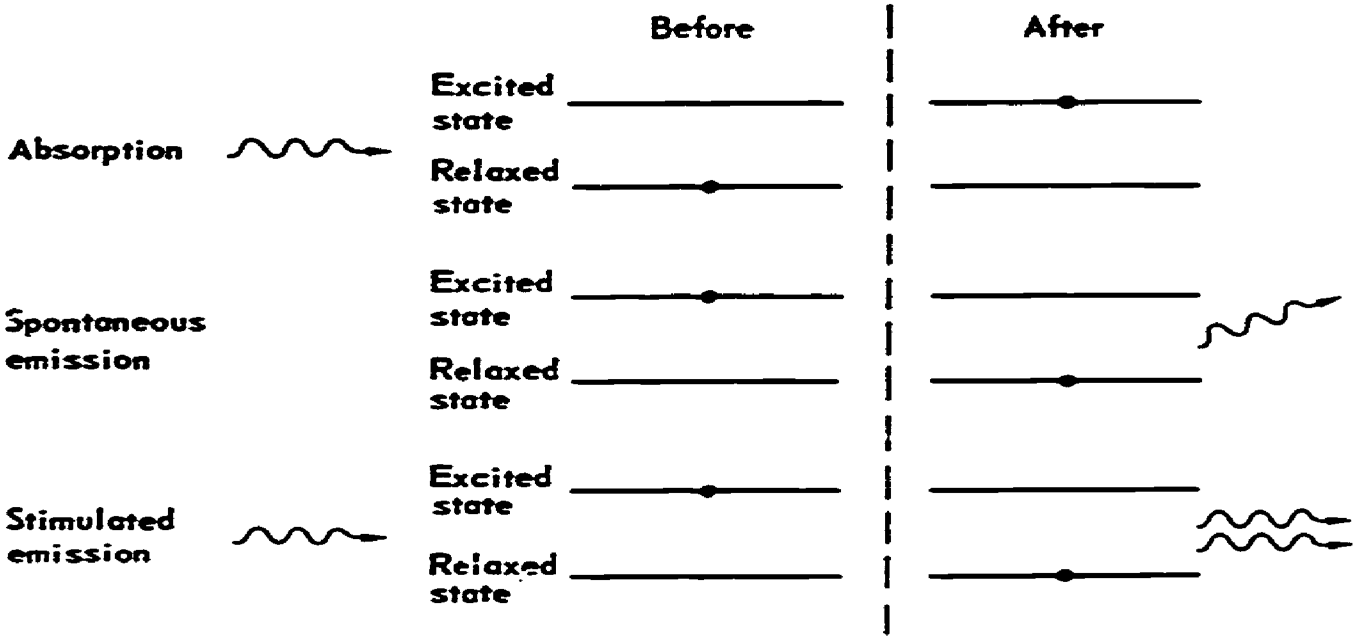

Figure 14 *An atom can release absorbed energy spontaneously or it can be stimulated to do so.*

Suddenly the answer came to him.

Normally more of the molecules in any substance are in low-energy states than in high ones. He would change the natural balance and create a situation with an abnormally large number of high-energy molecules. Then he would stimulate them to emit their energy by nudging them with microwaves. Here was amplification.

He could even take some of the emitted radiation and feed it back into the device to stimulate additional molecules, thereby creating an oscillator. This *feedback* arrangement, he knew, could be carried out in a cavity, which would resonate (just like an organ pipe) at the proper frequency. The resonator would be a box whose dimensions were comparable with the wavelength of the radiation, that is, a few centimeters on a side.

On the back of an envelope he figured out some of the basic requirements. Three years, and many experiments, later the maser (*m*icrowave *a*mplification by *s*timulated

emission of radiation) was a reality. The original maser was a small metal box into which excited ammonia molecules were added. When microwaves were beamed into the excited ammonia the box emitted a pure, strong beam of high frequency microwaves, far more temporally coherent than any that had ever been achieved before. The output of an ammonia maser is stable to one part in 100 billion, making it an extremely accurate atomic "clock".* Moreover, the amplifying properties of masers have been found to be very useful for magnifying faint radio signals from space, and for satellite communications.

Ammonia gas was chosen for the first maser because molecules of ammonia have two individual energy states that are separated by a gap corresponding in frequency to 23,870 megacycles (23,870 million cycles) per second. Ammonia molecules also react to a nonuniform electric field in ways that depend on their energy level: low-level molecules can be attracted and high-level ones repelled by the same field. Thus it is possible to separate the low-energy molecules from the high, and to get the excited molecules into the cavity without too much trouble.

This procedure for getting the majority of atoms or molecules in a container into a higher energy state, is called *population inversion* and is basic to the operation of both masers and lasers.

It should be noted that two Russians, N. G. Basov and A. M. Prokhorov, were working along similar lines independently of Townes. In 1952 they presented a paper at an All-Union (U.S.S.R.) Conference, in which they discussed the possibility of constructing a "molecular generator", that is, a maser. Their proposal, first published in 1954, was in many respects similar to Townes's. In 1955, Basov and Prokhorov discussed, in a short note, a new way to obtain the active atomic systems for a maser, a method that turned out to be of great importance.

*An atomic clock is a device that uses the extremely fast vibrations of molecules or atomic nuclei to measure time. These vibrations remain constant with time, consequently short intervals can be measured with much higher precision than by mechanical or electrical clocks.

Thus on October 29, 1964, the Nobel Prize in Physics was awarded, not only to Townes, but to Basov and Prokhorov as well. The award was for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the "aser" principle.

A LASER IS BORN

Following the maser development, there was much speculation about the possibility of extending the principle to the optical region. Indeed the first lasers—*l*ight *a*mplification by *s*timulated *e*mission of *r*adiation—were called "optical masers".

The difficulty, of course, was that optical wavelengths are so tiny—about 1/10,000 that of microwaves. The maser principle depended upon a physical resonator, a box a few centimeters (or even millimeters) in length. But at millimeter wavelengths, such resonators are already so small that they are hard to make accurately. Making a box 1/1,000 that size was out of the question. Another approach was necessary.

In 1958 A. L. Schawlow of Bell Telephone Laboratories and Dr. Townes outlined the theory and proposed a structure for an optical maser. They suggested that resonance could be obtained by making the waves travel back and forth along a relatively long, thin column of amplifying substance that had parallel reflectors at the ends.

After their theory of the optical maser had been published, the race to build the first actual device began in earnest. The winner, in 1960, was Dr. T. H. Maiman, then with Hughes Aircraft Company. (He is now president of Maiman Associates.) The active substance he used was a single crystal of ruby, with the ends ground flat and silvered.

Ruby is an aluminum oxide in which a small fraction of the aluminum atoms in the molecular structure, or lattice, have been replaced with chromium atoms. These atoms absorb green and blue light and hence impart a red color to the ruby. The chromium atoms can be boosted from their ground state into excited states when they absorb the green or blue light. This process, by which population inversion is achieved, has been given the name *pumping*.*

*The 1966 Nobel Prize in Physics was awarded to Prof. Alfred Kastler of the University of Paris for his research on optical pumping and studies on the energy levels of atoms.

Pumping in a crystal laser is generally achieved by placing the ruby rod within a spiral flash lamp (Figure 15) that operates like those used in high-speed (stroboscopic) photography. When the lamp is flashed, a bright beam of red light emerges from the ruby, shining out through one end, which has been only partially silvered.

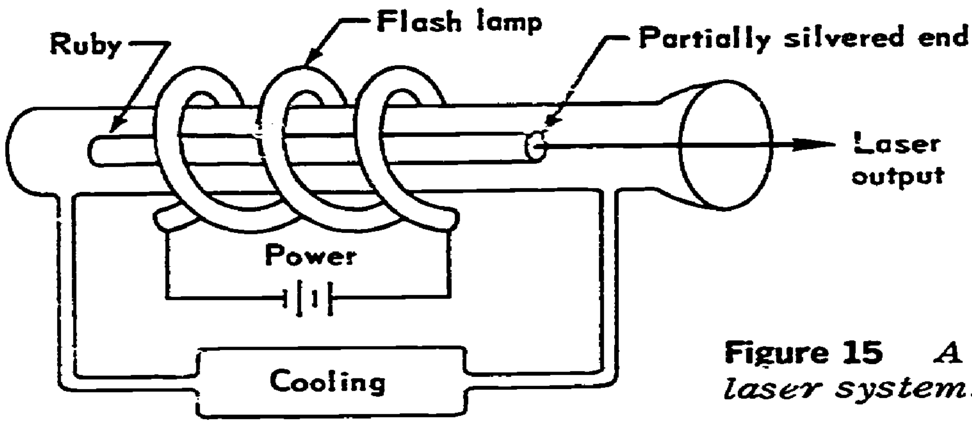

Figure 15 *A ruby laser system.*

The duration of this flash of red light is quite brief, lasting only some 300 millionths of a second, but it is very intense. In the early lasers, such a flash reached a peak power of some 10,000 watts.

When Maiman's device was successfully built and operating, a public relations expert was called in to help introduce this revolutionary device to the world. He took one look at the laser and decided that it was too small and insignificant looking and would not photograph well. Looking around the lab, he spotted a larger laser and decided that that one was better.

Dr. Maiman informed him in his best scientific manner that laser action had not been achieved with that one. But the world of promotion won out, and Dr. Maiman allowed the larger device to be photographed on the assumption—or was it hope?—that he would be able to get it to operate in the future. (He did.)

The device shown in Figure 16 is the true first laser. The all-important crystal rod is seen at the center. These crystals, incidentally, must be quite free of extraneous material; hence they are artificially "grown", as shown in Figure 17. The single large crystal is formed as it is pulled slowly from the "melt", after which it is ground to size and polished.

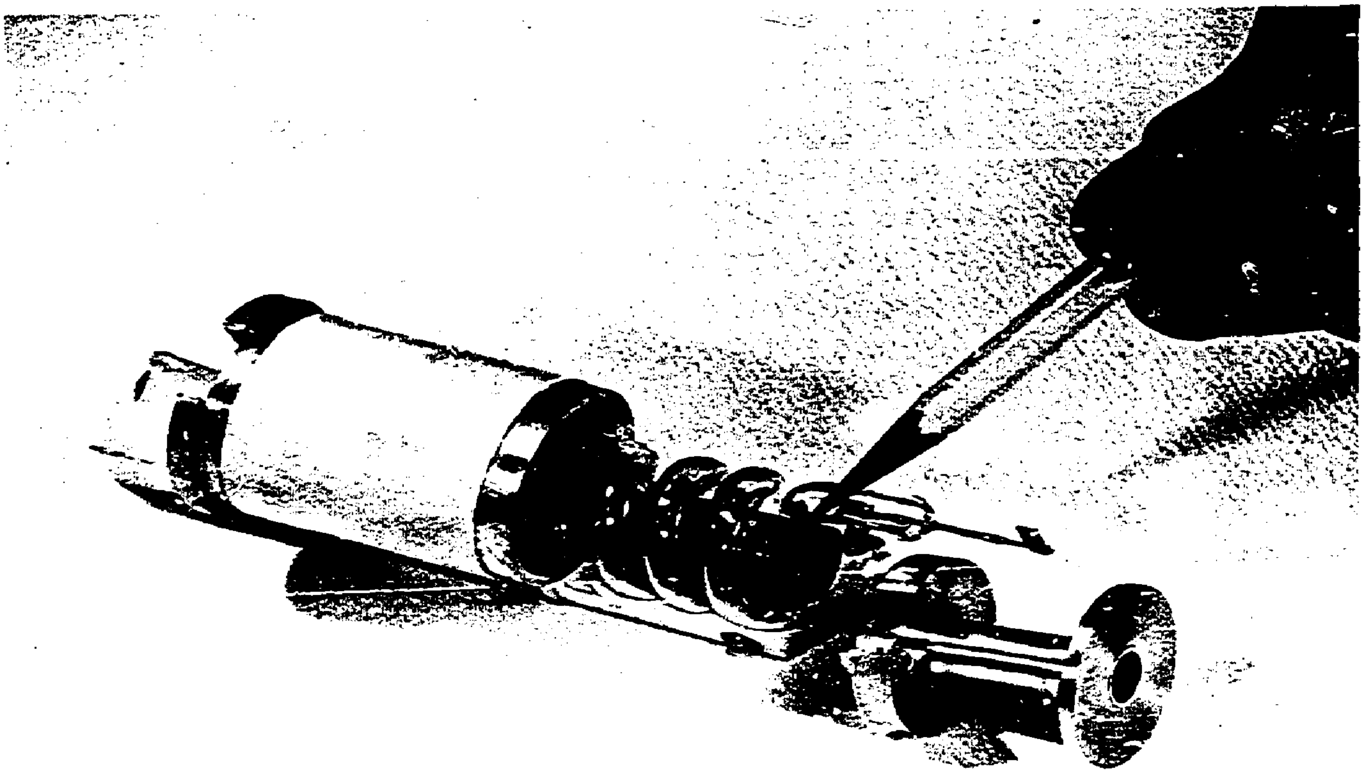

Figure 16 *Dr. Maiman's first laser. Output was 10,000 watts.*

Figure 17 *An exotic crystal of the garnet family is "grown" from a melt at a temperature of 3400°F.*

LASING—A NEW WORD

Now we can begin to put together the various processes and equipment we have been discussing separately. Perhaps the best way to do this is to look again at the word *laser* and recall its meaning: *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation. Our objective is to create a powerful, narrow, coherent beam of light. Let us see how to do this.

In Figure 18 we imagine a laser crystal containing many atoms in the ground state (white dots) and a few in the excited state (black dots). Pumping light (wavy arrows in *a*) raises most of the atoms to the excited state, creating the required population inversion.

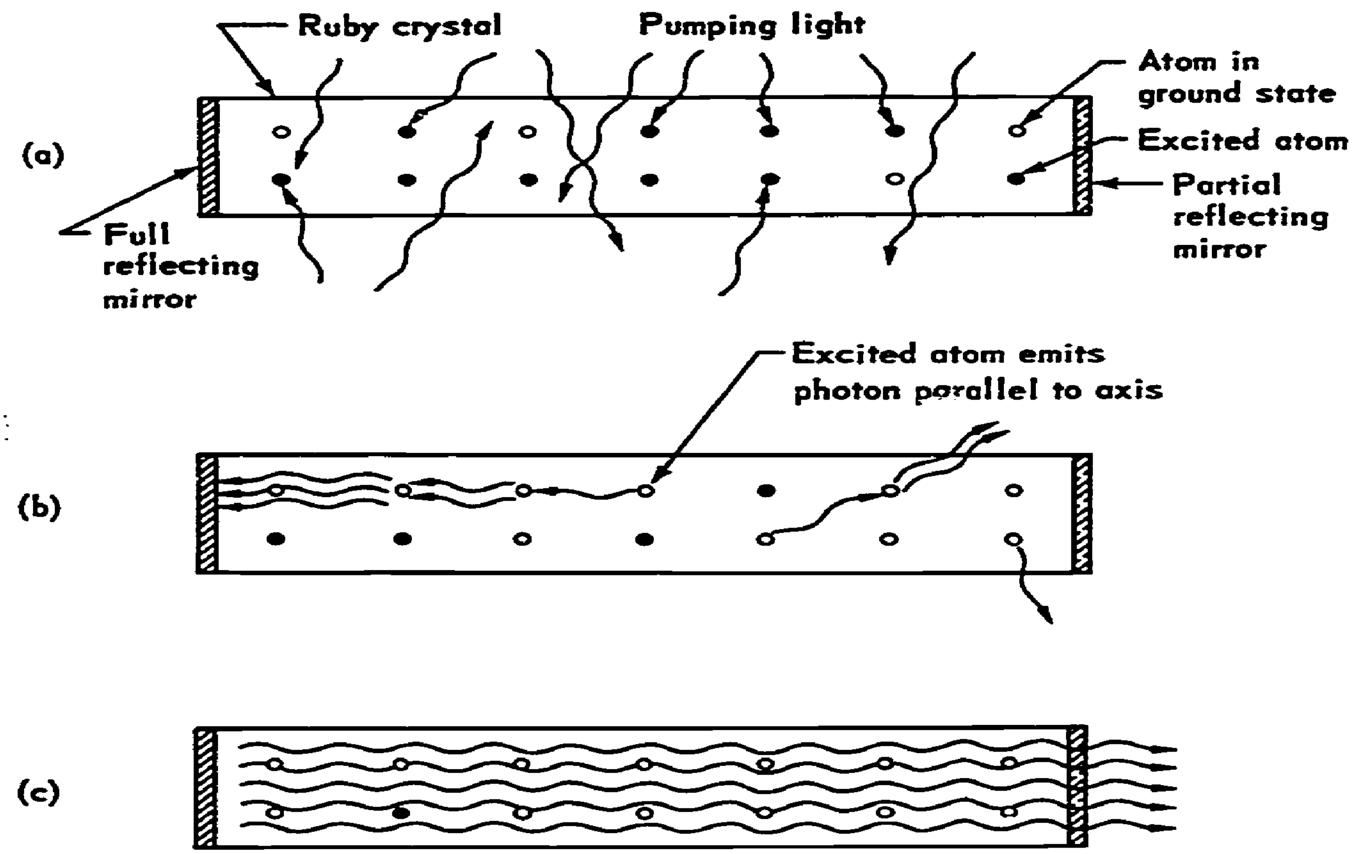

Figure 18 *Sequence of operations in a solid crystal laser. (a) Pumping light raises many atoms to excited state. (b) Lasing begins when a photon is spontaneously emitted along the axis of the crystal. This stimulates other atoms in its path to emit. (c) The resulting wave is reflected back and forth many times between the ends of the crystal and builds in intensity until finally it flashes out of the partially silvered end.*

Lasing begins when an excited atom spontaneously emits a photon parallel to the axis of the crystal (*b*). (Photons emitted in other directions merely pass out of the crystal.) The photon stimulates another atom in its path to contribute a second photon, in step, and in the same direction.

This process continues as the photons are reflected back and forth between the ends of the crystal. (We might think of lone soldiers falling into step with a column of marching men.) The beam builds up until, when amplification is great enough (c), it flashes out through the partially silvered mirror at the right—a narrow, parallel, concentrated, coherent beam of light, ready for...

SOME INTERESTING APPLICATIONS

Application of lasers can be divided into two broad categories: (1) commercial, industrial, military, and medical uses, and (2) scientific research. In the first case, lasers are used to do something that has been done in another way up to now (but not as well). Sometimes a laser solves a particular problem. For example, one of the first applications was in eye surgery, for "welding" a detached retina. The laser is particularly useful here because laser light can penetrate transparent objects such as the eye's lens (Figure 19), eliminating the need to make a cut into the eye.

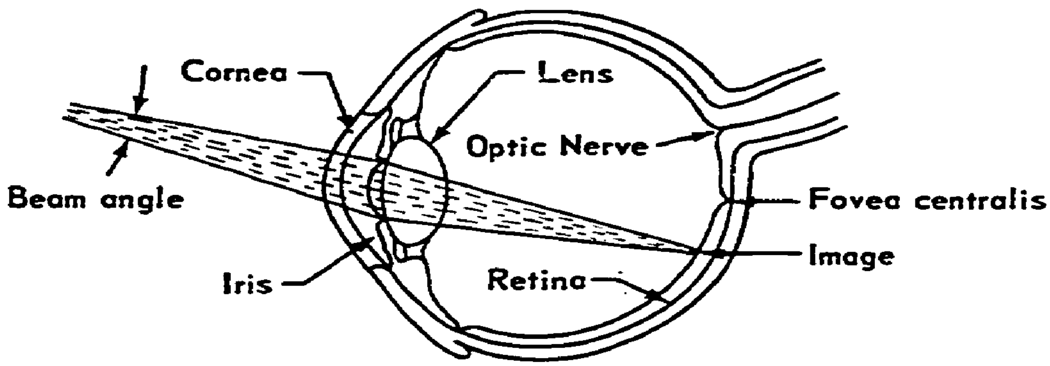

Figure 19 *Diagram of human eye showing laser beam focused on retina.*

Surgeons have long wanted a better technique for treating extremely small areas of tissue. A laser beam, focused into a small spot, performs perfectly as a lilliputian surgical knife. An additional advantage is that the beam, being of such high intensity, can also sterilize or cauterize tissue as it cuts.

The narrowness of the laser beam has made it ideal for applications requiring accurate alignment. Perhaps the ultimate here is the 2-mile-long linear accelerator built by Stanford University for the United States Atomic Energy Commission. "Arrow-straight" would not have been nearly good enough to assure expected performance. A laser beam was the only technique that could accomplish the incredible task of keeping the 7/8 inch bore of the accelerator straight along its 2-mile length. A remote monitoring system, based on the same laser beam, tells operators when a

section of the accelerator has shifted out of line (due for example to small earth movements) by more than about $^1/_{32}$ inch—and identifies the section.*

Figure 20 shows the 2-mile-long "klystron gallery" that generates the power for kicking the high-energy particles down the tube. The gallery parallels the accelerator housing and lies 25 feet beneath it (Figure 21). The large tube houses the optical alignment system and supports the smaller accelerator tube above. Target patterns dropped into the large tube at selected points produce an interference pattern at the far end of the tube similar to the one in Figure 14. Precise alignment of the tube is achieved by aiming the laser at the center dot of the pattern. Then the section that is out of line is physically moved until the dot appears in the proper place at the other end of the tube. It is the extreme coherence of the laser beam that makes this technique possible.

Having heard that laser light has bored through steel and is being used in microwelding, some have asked whether the laser will ever be used to weld bridge members and other structural girders. This is missing the whole point of the laser: It would be like washing your floor with a toothbrush (even one with extra stiff bristles)! There would be no advantage to using lasers for large-scale welding; present equipment for this operation is quite satisfactory and far less wasteful of input power. The sensible approach is to use lasers where existing processes leave something to be desired.

Until the advent of the laser, for example, there was no good way to weld wires 0.001 inch in diameter. Nor was there a good way to bore the tiny hole in a diamond that is used as a die for drawing such fine wire. It used to take 2 days to drill a single diamond. With laser light the operation takes 2 minutes—and there is no problem with rapid wear of a cutting tool.

So much for the first category of application. In the second category, namely use of the laser as a scientific tool, we enter a more theoretical domain. Here we use

*See *Accelerators*, a companion booklet in this series, for a full account of the Stanford "Atom Smasher".

Figure 20 *A laser beam was used (and continues to be used) for precise alignment of Stanford University's 2-mile-long linear accelerator. This view shows the aboveground portion during construction.*

coherent light as an extension of ourselves, to probe into and to look at the world around us.

Much experimental science is a matter of cooling, heating, grinding, squeezing, or otherwise abusing matter to see how it will react. With each new tool—ultrafast centrifuges, high- and low-pressure and extreme-temperature chambers, intense magnetic fields, atomic accelerators and so on—more has been learned about this still-puzzling world.

Since coherent light is something new, we can do things to matter that have not been done before, and see how it reacts. The laser is being used to investigate many problem areas in biology, chemistry, and physics. For example, sound waves of extremely high frequency can be generated in matter by subjecting it to laser light. These intense vibrations may have profound effects on materials.

In the chemical field the sharp beam and monochromatic energy of the laser hold great promise in the exploration

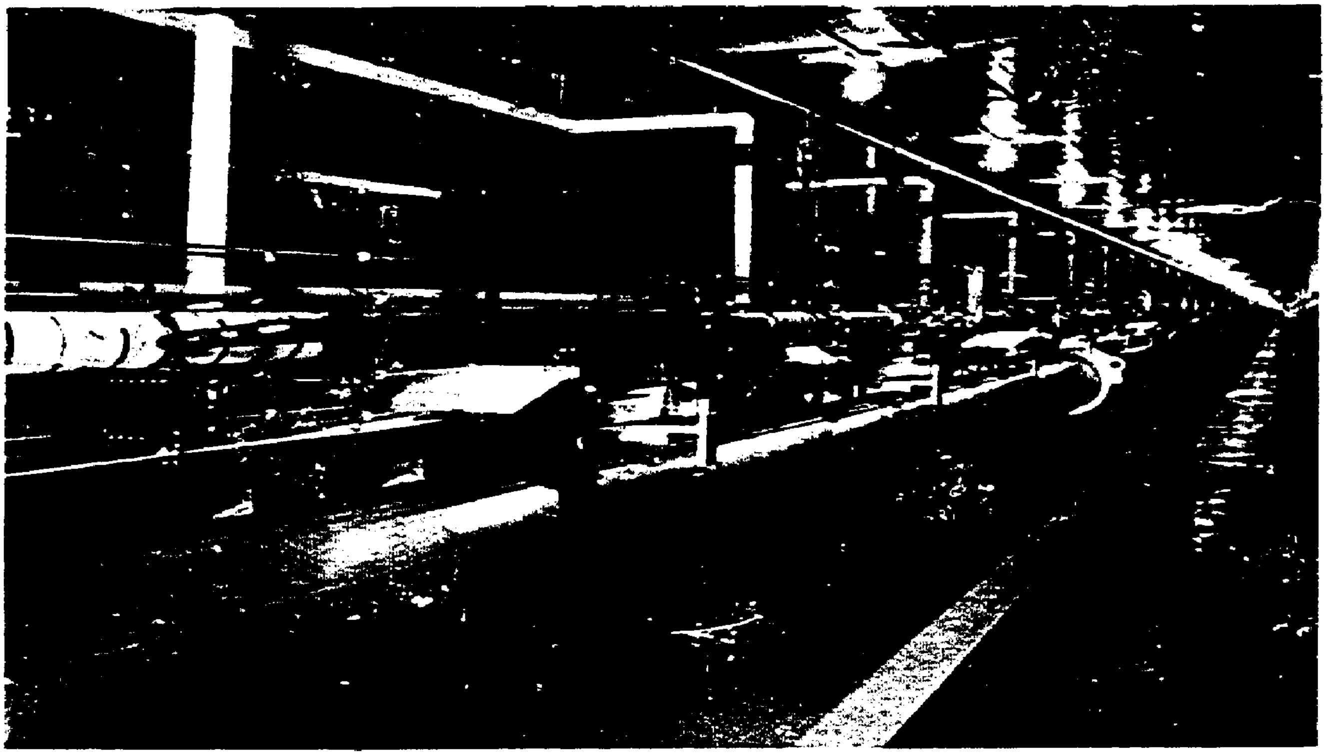

Figure 21 *Subterranean view of Stanford accelerator housing. Alignment optics (laser systems) are housed in the large tube, which also acts as support for the smaller accelerator tube above it.*

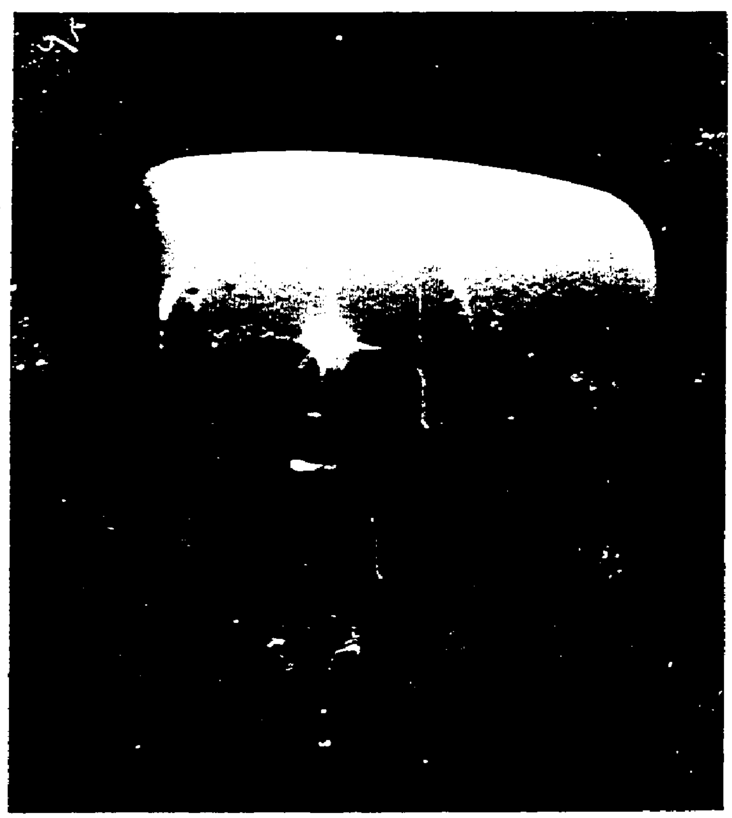

Figure 22 *Laser beam spot as observed at the end of the accelerator.*

of molecular structure and the nature of chemical reactions. Chemical reactions usually are set off by heat, agitation, electricity, or other broadly applied means. None of these energizers allow the fine control that the laser beam does. Its extremely fine beam can be focused to a tiny spot, thus allowing chemical activity to be pinpointed. But there is a second advantage: The monochromaticity of coherent light also makes it possible to control the energy (in addition to the intensity) of the beam accurately by simply varying the wavelength. Thus it may be possible, for instance, to cause a reaction in one group of molecules and not in another.

One application in chemistry that holds great promise is the use of laser energy for causing specific chemical reactions such as those involved in the making of plastics. Bell Telephone Laboratory scientists have changed the styrene monomer (a "raw" plastic material) to its final state, polystyrene, in this way. The success of these and similar experiments elsewhere opens for exploration a vast area of molecular phenomena.

In another scientific application, the laser is being used more and more as a teaching tool. Coherence is a concept that formerly had to be demonstrated by diagrams, formulas, and inference from experiments. The laser makes it possible to see coherence "in action", along with many of the physical effects that result from it. Such phenomena as diffraction, interference, the so-called Airy disc patterns, and spatial harmonics, always difficult to demonstrate to students in the abstract, can now be *seen* quite concretely.

Other interesting things can also be seen more plainly now. At the Los Alamos Scientific Laboratory, laser light is being used to "look" at plasmas; the result of one such look is shown in Figure 23. Plasmas are ionized gaseous mixtures. Their study lies at the heart of a constant search by atomic scientists for a self-sustained, controlled fusion reaction that can be used to provide useful thermonuclear power. This kind of reaction provides the almost unlimited energy in the sun and other stars. It is more efficient and releases less radioactivity than the other principal nu-

Figure 23 *Shadowgraph of deuterium discharge taken in laser light. Turbulence of the plasma is clearly seen.*

clear process, fission, which is used in atomic-electric power plants.*

Westinghouse Electric Corporation scientists, on the other hand, have used the concentrated energy of the laser, not to look at, but to *produce* a plasma (Figure 24). They blasted an aluminum target the size of a pinhead with a laser beam, thereby vaporizing it and creating a plasma. The calculated temperature in the electrically charged gas was 3,000,000° centigrade. This is pretty hot, but still not hot enough for a thermonuclear reaction.

*For descriptions of fission and fusion processes, see *Controlled Nuclear Fusion*, *Nuclear Reactors*, and *Nuclear Power Plants*, other booklets in this series.

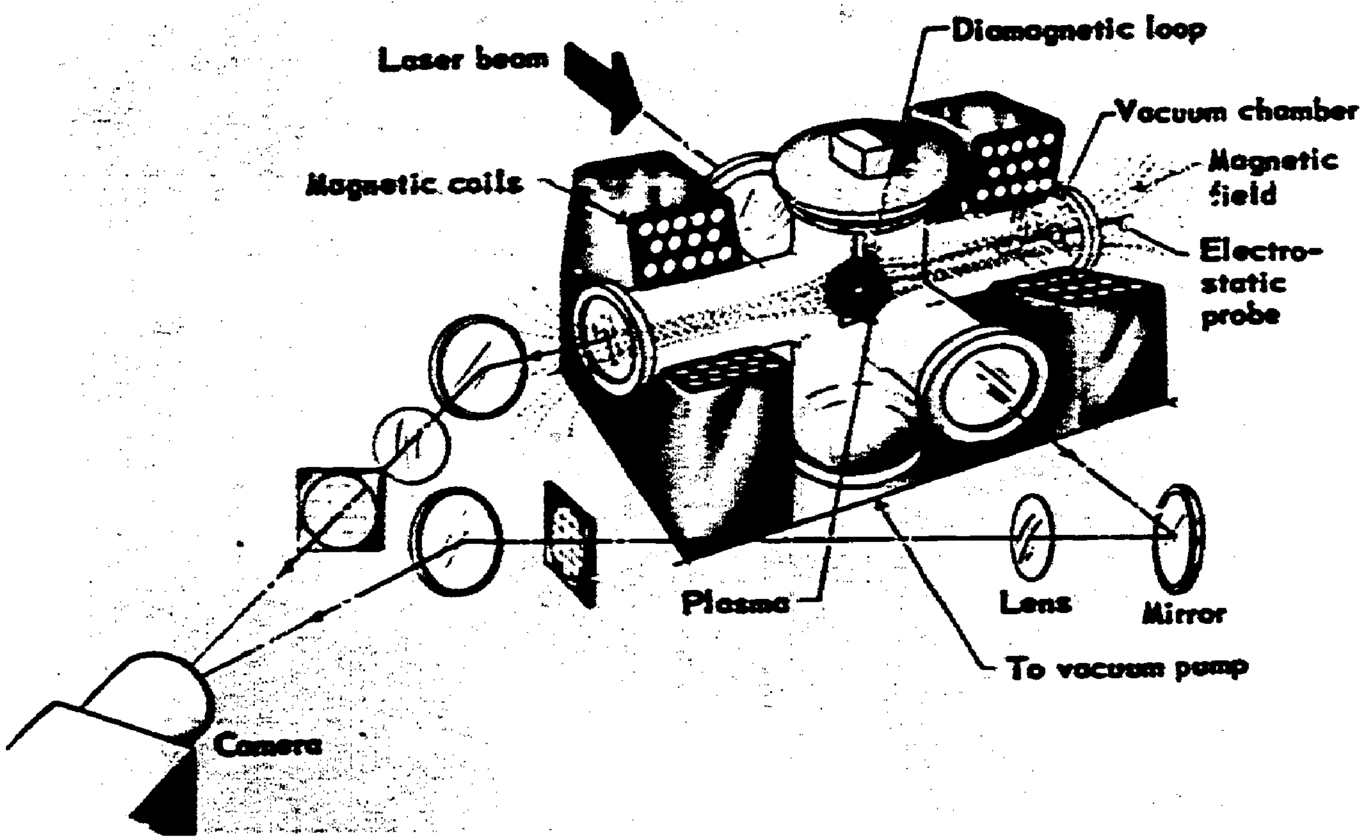

Figure 24 *Plasma heating by laser light.*

The temperature of a plasma necessary to sustain a thermonuclear reaction is so high (above 10,000,000°C) that any material is vaporized instantly on coming into contact with it. The only means developed so far to contain the plasma is an intense magnetic field, or "magnetic bottle"; containment has been accomplished for only a few thousandths of a second at most. The objective of the Westinghouse research, which was supported by the Atomic Energy Commission, was to study in detail the interaction of the plasma with a magnetic field.

We do not have room to describe more applications in detail, but it may be interesting to list a few other uses of lasers—some commercial and some still experimental:

- Earthquake prediction.
- Measurement of "tides" in the earth's crust under the sea.
- Laser gyroscopes.
- Highly accurate velocity measurement (useful in certain assembly line and continuous manufacturing processes).

- Scanner for analyzing photographs of bubble chamber tracks and astronomical phenomena.
- Computer output and storage systems; perhaps even complete optical data processing systems.
- Lightning-fast printing devices.
- High-speed photography (Figure 25).
- Missile tracking and accurate alignment of antennas.
- Automatic flaw spotter for big radio antennas.
- Aircraft landing aid for poor weather conditions.
- Fast, painless dental drill.
- Cancer research.

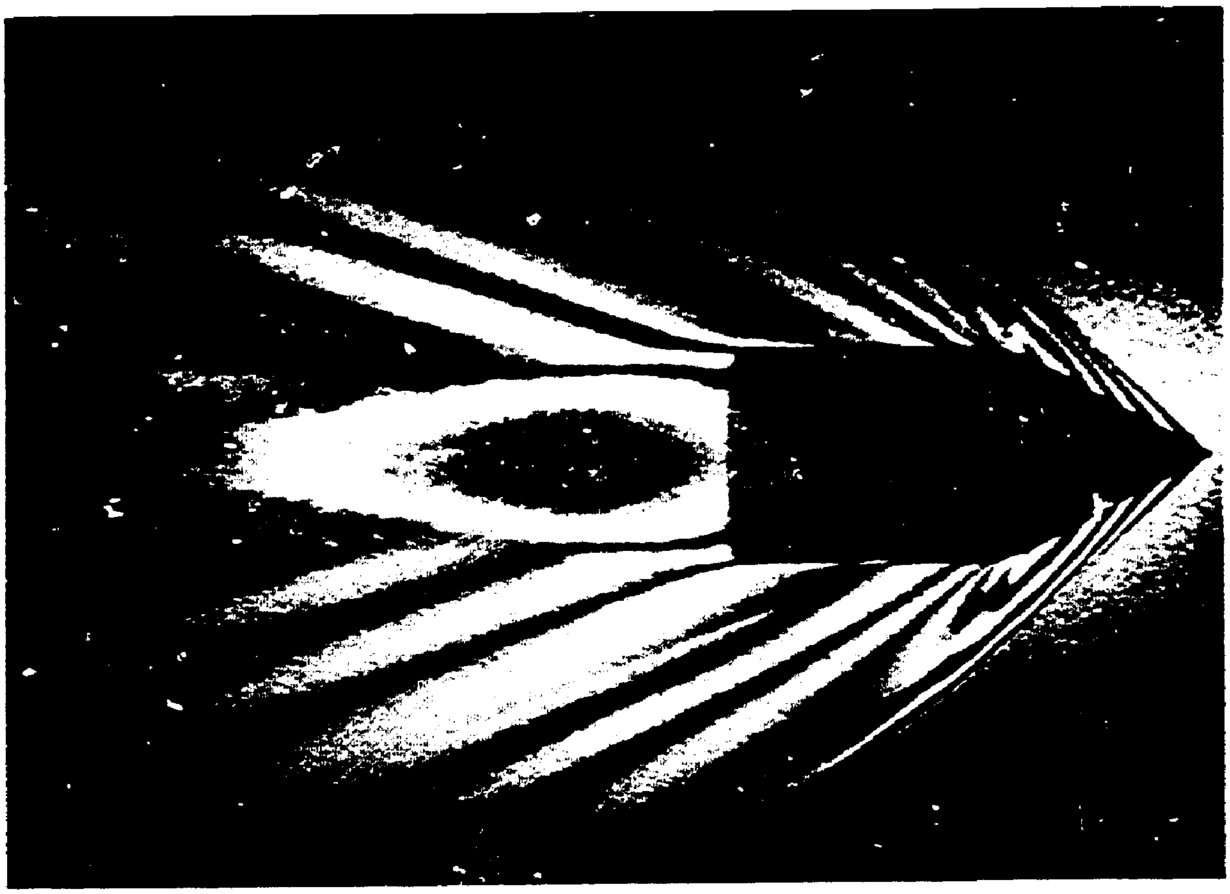

Figure 25 *Twenty-two caliber bullet and its shock wave are photographed from the image produced by a doubly exposed laser hologram. The original hologram was exposed twice by a ruby laser within half a thousandth of a second as the bullet sped past at $2^1/_2$ times the speed of sound.*

A MULTITUDE OF LASERS

It is almost self-evident that no single device, even one as incredible as the laser, could accomplish all the feats mentioned in the preceding paragraphs. After all, some of these applications require high power but not extremely high monochromaticity, while in others the reverse may be true. Yet, by its very nature, any laser produces a beam with one, or at the most a few, wavelengths, and many different materials would be needed to provide the many different wavelengths required for all the tasks listed.

Also, the first laser was a pulsed device. Light energy was pumped in and a bullet of energy emerged from it. Then the whole process had to be repeated. Pulsed operation is fine for spot-welding and for applications such as radar-type rangefinding, where pulses of energy are normally used anyway. With lasers smaller objects can be detected than when using the usual microwaves. But a pulsed process is not useful for communications. In other words, pulsing is good for certain applications but not for others.

And of course solid crystals are difficult to manufacture. Hence, it was natural for laser pioneers to look hopefully at gases. Gas lasers would be easier to make—simply fill a glass tube with the proper gas and seal it.

But other advantages would accrue. For one thing the relatively sparse population of emitting atoms in a gas provides an almost ideally homogeneous medium. That is, the emitting atoms (corresponding to chromium in the ruby crystal) are not "contaminated" by the lattice or host atoms. Since only active atoms need be used, the frequency coherence of a gas laser would probably be even better than that of the crystal laser, they reasoned.

It was less than a year after the development of the ruby laser that Ali Javan of Bell Telephone Laboratories proposed a gas laser employing a mixture of helium and neon gases. This was an ingeniously contrived partnership whereby one gas did the energizing and the other did the amplifying. Gas lasers now utilize many different gases for different wavelength outputs and powers and provide the "purest" light of all. An additional advantage is that

the optical pumping light could be dispensed with. An input of radio waves of the proper frequency did the job very nicely.

But most significant of all, Javan's gas laser provided the first continuous output. This is commonly referred to as CW (continuous wave) operation. The distinction between pulsed and CW operation is like the difference between baking one loaf of bread at a time and putting the ingredients in one end of a baking machine and having a continuous loaf emerge at the other.

When a non-expert thinks of a laser, he is apt to think of power—blinding flashes of energy—as illustrated in Figure 26. As we know, this is only a small part of the capability of the laser. Nevertheless, since lasers are often specified in terms of power output it may be well to discuss this aspect.

The two units generally used are *joules* and *watts*. You are familiar with a watt and have an idea of its magnitude: think, for example, of a 15-watt or a 150-watt bulb. A watt is a unit of *power;* it is the rate at which (electrical) work is being done.

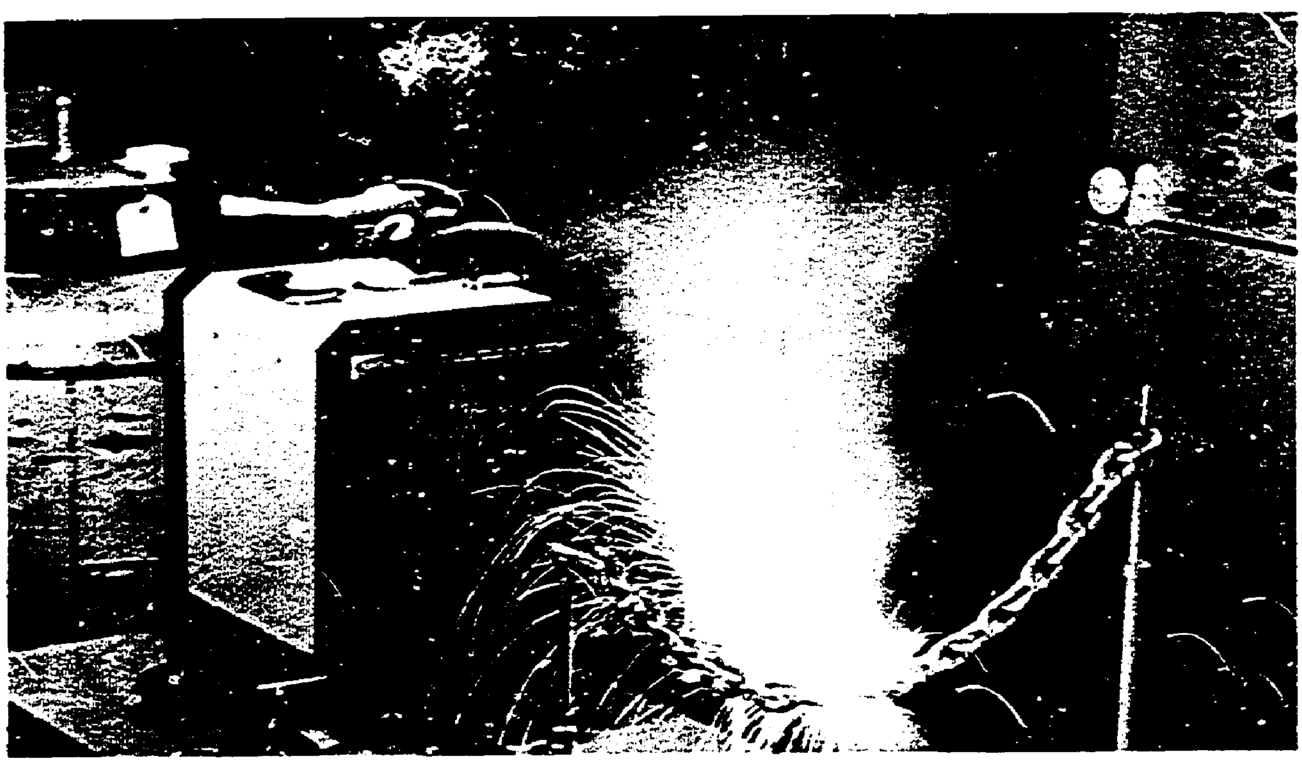

Figure 26 *High power is demonstrated as a laser beam blasts through metal chain.*

The joule is a unit of *energy* and can be thought of as the total capacity to do work. One joule is equivalent to 1 watt-second, or 1 watt applied for 1 second. But it can also mean a 10-watt burst of laser light lasting 0.1 second, or a billion watts lasting a billionth of a second.

In general, the crystal (ruby) lasers are the most powerful, although other recently introduced materials, such as liquids (see Figure 27) and specially prepared glass, are providing competition. With proper auxiliary equipment, bursts of several *billion* watts have been achieved; but the burst lasts only about 100 millionths of a second. For certain uses, that's just what is wanted: a highly concentrated burst of energy that does its work without giving the material being "shot" a chance to heat up and spread the energy, perhaps damaging adjacent areas.

Figure 27 *Active substance for a modern liquid laser is made in an uncomplicated 10-minute procedure. Bluish powder of the rare earth, neodymium, is dissolved in a solution of selenium oxychloride and sealed in a glass tube.*

Since the joule gives a measure of the total energy in a laser burst it is not applicable to CW output. Power in this area began low—in the milliwatt (one thousandth of a watt) region—but has been creeping up steadily. A recent gas laser utilizing carbon dioxide has already reached 550 watts of continuous infrared radiation. This is the giant 44-footer shown in Figure 28. An advantage of gas (and liquid) lasers is that they can be made just about as large as one wishes. By way of comparison, the smallest gas laser in use is shown in Figure 29.

Figure 28 *A giant 44-foot gas laser produces 550 watts of continuous power and is expected to reach 1000 watts. Glowing of the tube comes from gas discharge, not from laser light, which is in the infrared region and cannot be seen.*

One of the least satisfactory aspects of the laser has been its notoriously low efficiency. For a while the best that could be accomplished was about 1%. That is, a hundred watts of light had to be put in to get 1 watt of coherent light out. In gas lasers the efficiency was even lower, ranging from 0.01% to 0.1%.

In gas lasers this was no great problem since high power was not the objective. But with the high-power solid lasers, pumping power could be a major undertaking. A high-

power laser pump built by Westinghouse Research Laboratories handles 70,000 joules. In more familiar terms, the peak power input while the pump is on is about 100,000,000 watts. For a brief instant this is roughly equal to all the electrical power needs of a city of 100,000 people.

Two relatively new developments have changed the efficiency levels. One, the carbon dioxide gas laser, is quite efficient, with the figure having passed 15%. The second is the injection, or semiconductor laser, in which efficiencies of more than 40% have been obtained. Unless unforeseen difficulties arise this figure is expected to continue to rise to a theoretical maximum of close to 100%.

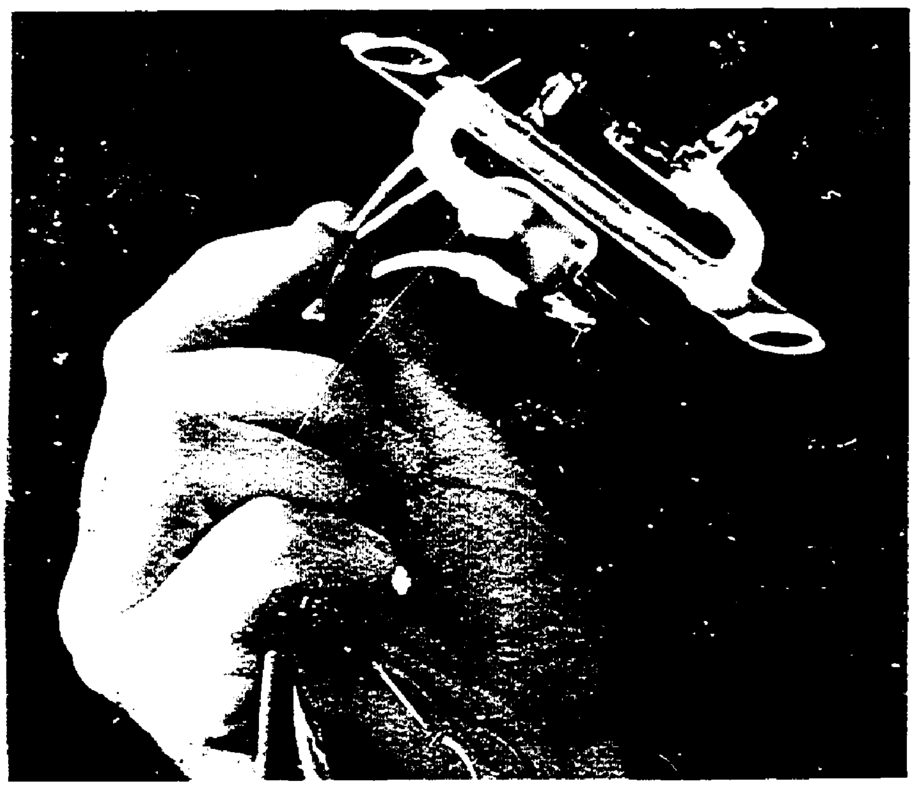

Figure 29 *A miniature gas laser produces continuous output in visible red region.*

The semiconductor laser is to solid and gas lasers what the transistor was to the vacuum tube; all the functions of the laser have been packed into a tiny semiconductor crystal. In this case, electrons and "holes" (vacancies in the crystal structure that act like positive charges) accomplish the job done by excited atoms in the other types. That is, when they are stimulated they fall from upper energy states to lower ones, and emit coherent radiation in the process. Aside from this the principle of operation is the same.

The device itself, however, is vastly different. For one thing it is about the size of this letter "o" (Figure 30). For another, it is self-contained; since it can convert electric current directly into laser light—the first time this has been possible—an external pumping source is not required. This makes it possible to modulate the beam by simply modulating the current. (A different approach has been to modulate a magnetic field around the device. This, it turns out, can also be done with some newer solid crystal lasers.)

An additional advantage offered by the semiconductor laser is simplicity. There are no gases or liquids to deal with, no glassware to break, and no mirrors to align. Although it will not deliver high power, it can already deliver enough CW power for certain communications purposes. Its simplicity, efficiency, and light weight make it ideal for use in space.

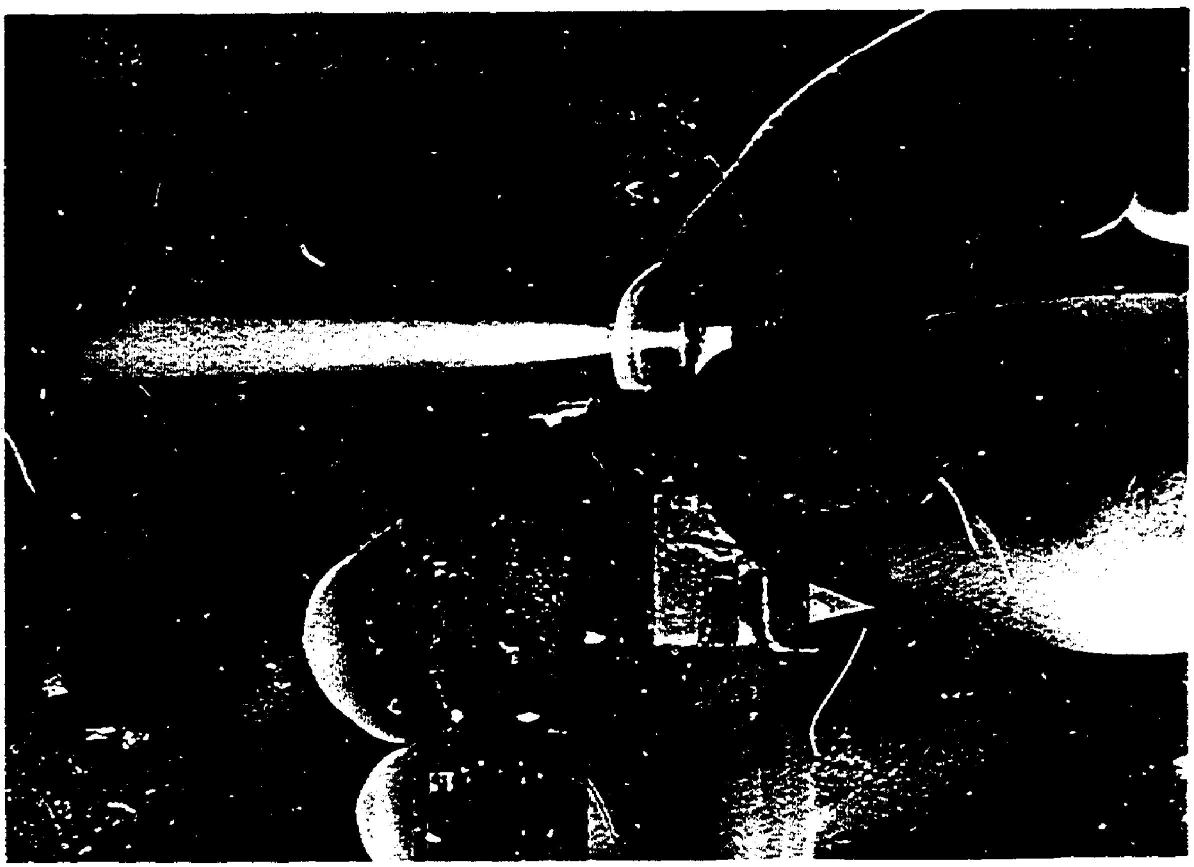

Figure 30 *A tiny injection laser works in infrared region. The beam is visible because photo was taken with infrared film. The laser itself is a tiny crystal of gallium arsenide inside the metal mount being held between the fingers.*

COMMUNICATIONS

Future deep space missions are expected to require extremely high data transmission rates (on the order of a million bits* per second) to relay the huge quantities of scientific and engineering information gathered by the spacecraft. Higher data rates are necessary to increase both the total capacity and the speed of transmission. By comparison, the Mariner-4 spacecraft that sent back TV pictures of Mars had a data rate of only eight bits per second—a hundred thousand times too small for future missions. The use of lasers would mean that results could be transmitted to earth in seconds instead of the 8 hours it took for the photos to be sent from Mariner-4.

One of the problems to be solved in using lasers for deep space communication, oddly enough, is that of pointing accuracy. Since the beam of laser energy is narrow, it would be possible for the radiation to miss the earth altogether and be lost entirely unless the laser were pointed at the receiver with extreme precision. Aiming a gun at a target 50 yards away is one thing; aiming a laser from an unmanned spacecraft 100 million miles away is quite another. It is believed, however, that present techniques can cope with the problem.

Another peculiarity of laser communication is that it will probably be accomplished faster and more readily in space than here on earth. Powerful though laser light may be, it *is* light and is therefore impeded to some extent by our atmosphere even under good conditions. Data transmissions of 20 and 30 miles have already been accomplished in good weather with lasers.

But if you have ever tried to force a searchlight beam or shine automobile headlights through heavy fog, rain, or snow, you will appreciate the magnitude of the problem under these conditions. The use of infrared frequencies helps to some extent, since infrared is somewhat more penetrating, but the poor-weather problem is a serious one.

*A bit is a digit, or unit of information, in the binary (base-of-two) system used in electronic data transmission systems.

A possible solution is the use of "light pipes", similar to the wave guides already in use for certain microwave applications over short distances. But as often happens, new developments create new needs; how, for example, can we get the laser beam to stay centered in the pipe and follow curves? A series of closely spaced lenses, about 1000 per mile, probably would accomplish this, but too much light would be lost by scattering from the many lens surfaces.

Scientists are experimenting with a new kind of "lens", one that uses variations in the density of gases to focus and guide the beam automatically. Since there are no surfaces in the path of the light beam, and since the gas is transparent and free of turbulence, the laser beam is not appreciably weakened or scattered as it travels through the pipe.

Figure 31 shows how the gas focusing principle might be used to guide a beam through a curving pipe. The shading represents the density of the gas. Several means have been developed to keep the gas denser in the center than

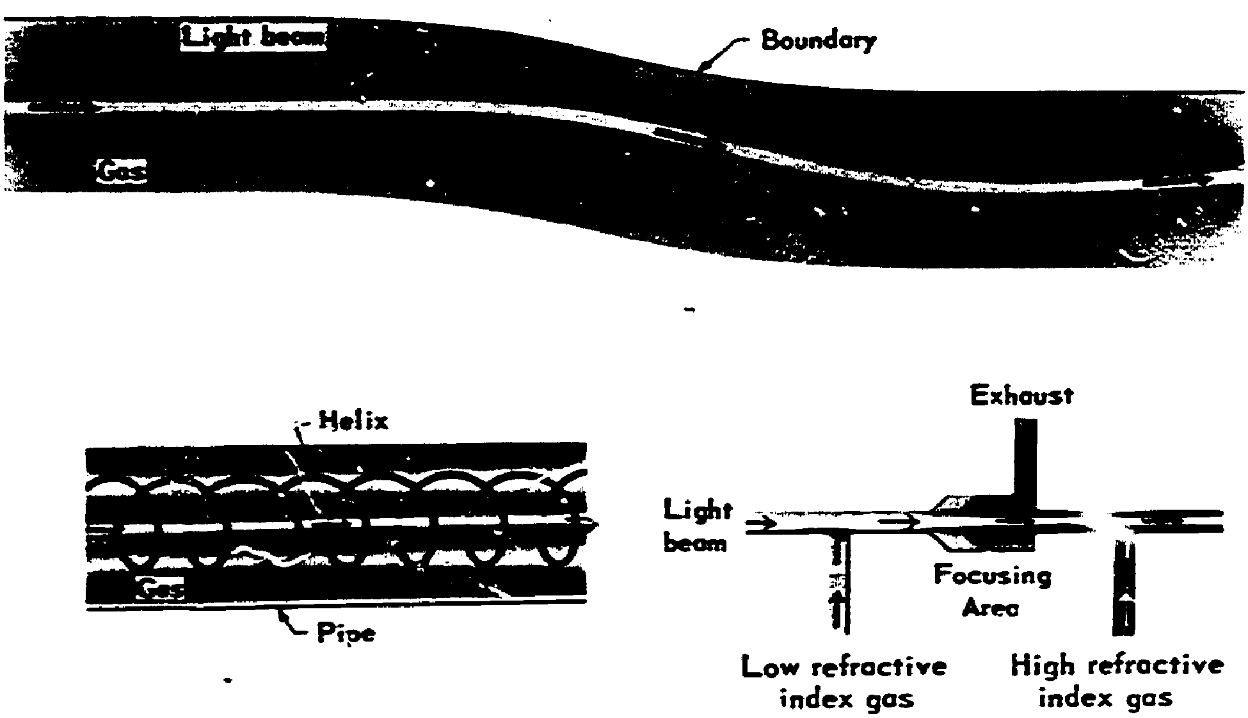

Figure 31 *Laser light beam being guided through a "light pipe" by a gas "lens". Heating coil (lower left) or mixture of gases (lower right) are two possible ways of maintaining proper density gradient in the gas.*

around the outside. When the pipe curves, the light beam starts moving off the axis of the pipe. The gas then acts like a prism, deflecting the light beam in the direction of the curvature of the "prism".

In communication between distant space and earth, a light pipe might be a little cumbersome; hence it may prove necessary to set up an intermediate orbiting relay station that will, particularly in cases of poor weather, intercept the incoming laser beam and convert it to radio frequencies that can penetrate our atmosphere with greater reliability.

Powering space-borne lasers will, of course, be a problem. Indeed one of the major unsolved problems in production of spacecraft and long-term satellites is the provision of an adequate supply of power. Fuel cells and solar cells have helped but do not give the whole answer.*

One other approach has already been developed: a sun-pumped laser. Sunlight focused onto the side of the laser (see Figure 32) provides the pumping power, enabling the device to put out 1 watt of continuous infrared radiation, enough for special space applications. Descendents of this device could produce visible light if this is deemed desirable.

Another approach, using *chemical lasers*, is even more intriguing and may have greater consequences. Chemical lasers will derive their energy from their internal chemistry rather than from the outside. A mixture of two chemicals may be all that is needed to initiate laser action aboard a spacecraft or satellite. (Chemical lasers also offer the promise of even greater concentrations of power than have been achieved heretofore, which may make them useful in plasma research.)

With all these possibilities, it may still be that spacecraft will need more power than is available on board. The narrow beam of the laser offers one more fascinating possibility, especially in the case of satellites relatively near earth. The light of a laser might actually be used to am energy to a receiver, either for immediate use or

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*See *SNAP, Nuclear Space Reactors* and *Power from Radioisotopes*, other booklets in this series, for descriptions of nuclear sources of power for space.

storage. It would then become possible to "refuel" satellites at will, giving them much greater capabilities.

If available laser power is great enough, laser beams might even be used to push satellites back into their proper orbits when they begin to wander off course, as they almost invariably do after a while.

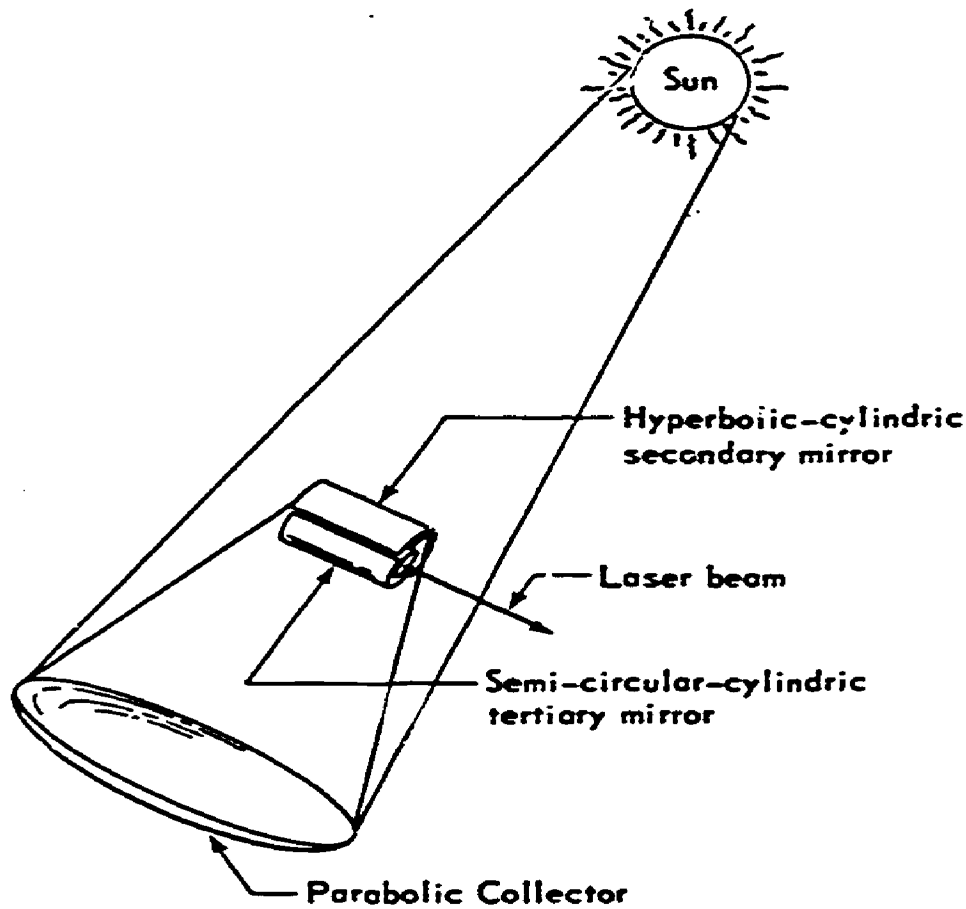
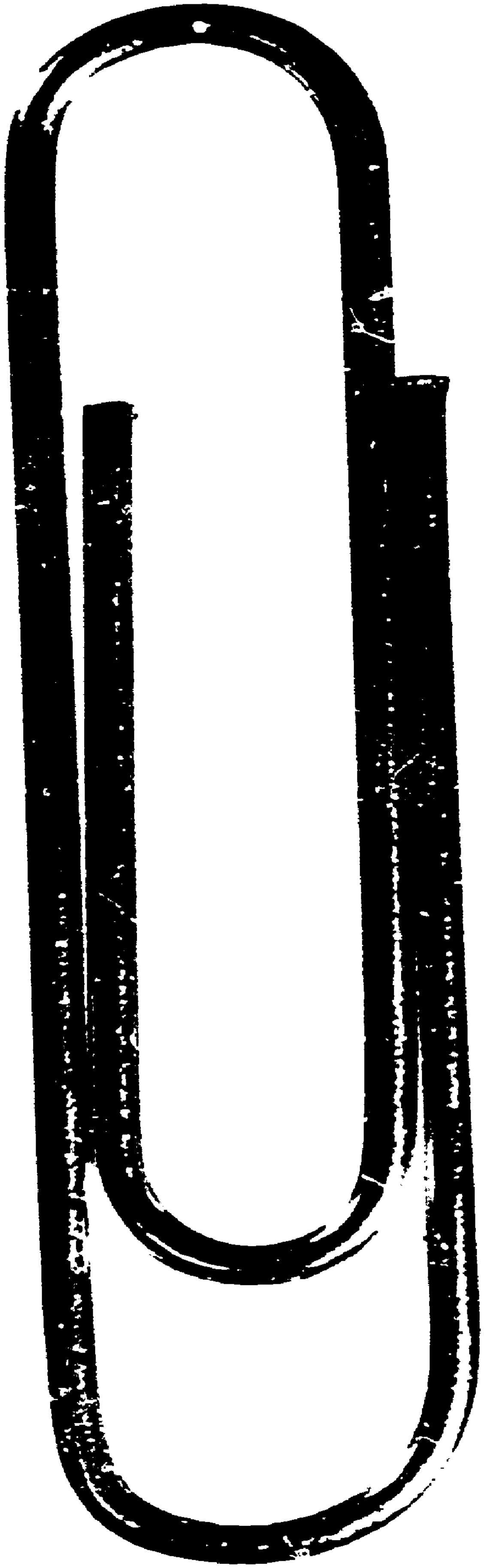


Figure 32 *Artist's rendering of sun-pumped laser as it would operate in space. The sun's rays are collected by a parabolic reflector and are focused on the laser's surface by two cylindrical mirrors.*



A LASER IN YOUR FUTURE?

Atomic energy, only a scientific dream a few short years ago, is now providing needed power in many parts of the world. In the same way, the laser, also an atomic phenomenon, has made its way out of the laboratory and into the fields of medicine, commerce, and industry. If it hasn't touched your life as yet, you need only be patient. It will.

Indeed the most exciting probability of all is that lasers undoubtedly will change our lives in ways we cannot even conceive of now.

Figure 33 *Tiny hole drilled in paper clip demonstrates remarkable capability of laser beam. Paper clip is $1^1/_4$ inches long. Hole (top) was drilled by the laser microwelder shown in Figure 1.*

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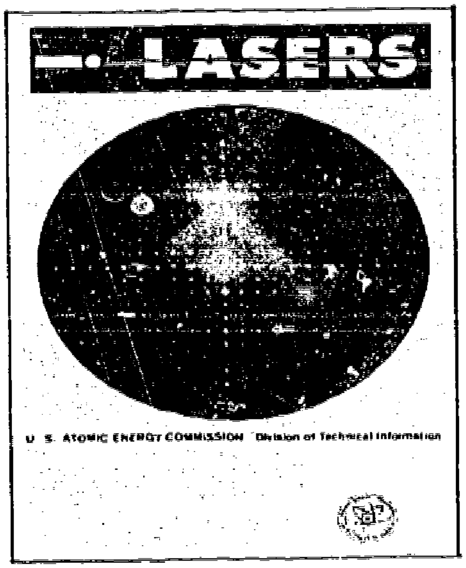

THE COVER

A laser beam, pointed at the camera through a screen, formed this pattern of light. The regularly spaced separate dots reveal the extreme order, or coherence, of laser light—one of its many unique qualities explained in this booklet. The star-like pattern was formed by the beam's passage through the closely woven mesh of the screen. (The operator's shadow can be seen at the right.)

THE AUTHOR

HAL HELLMAN is a free-lance science writer. Although he writes for both specialists and the non-technical public (including young adults), he prefers to interpret science for the latter, believing that it is both more difficult and more rewarding. The titles of some of his books, published or forthcoming, reflect a wide range of interests—*Navigation: Land, Sea and Sky, Light and Electricity in the Atmosphere, The Art and Science of Color, Defense Mechanisms: From Virus to Man, Controlled Guidance Systems, High Energy Physics*, and *Spectroscopy*, another booklet in this series.

Prior to going into full-time writing, Mr. Hellman was with General Precision, Inc., for 10 years. During the second five-year period he was manager of Information Services, and it was during that time that his interest in science writing began.

Mr. Hellman holds a B.A. in Economics, an M.A. in Industrial Management, and an M.S. in Physics. He is a member of the National Association of Science Writers.

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